REPORT METEOROLOGY AND CLIMATOLOGY No. 120, 2023

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A national study for 2019 based on dispersion modelling from regional down to street canyon level

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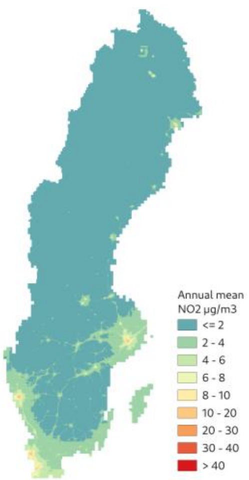

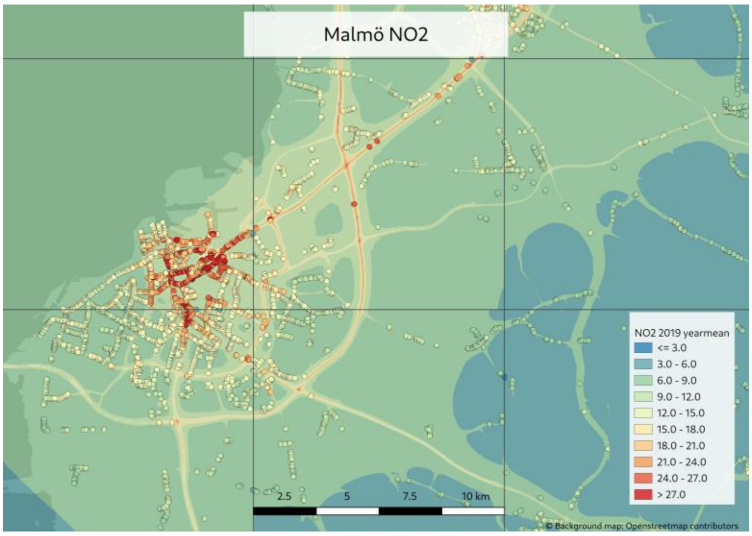

Front:
Annual mean concentrations of NO_2 over Sweden and zoomed in over Malmö for 2019.

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Client: Swedish Transport Administration (Trafikverket), Swedish Environmental Protection Agency (Naturvårdsverket)

Summary

In this development project, concentrations of NO_2, PM10 and PM2.5 have been calculated for the whole of Sweden for the year 2019. Simulations have been made with a new methodology that enables an almost completely seamless combination of dispersion modelling on three scales; regional, urban and street scale, without double counting emissions. Pollution levels have been calculated at 50x50 m^2 resolution, which provides a complete and detailed dataset at a national level. The spatial resolution of 50 m captures concentration gradients important for high-resolution exposure calculations. A strength of using dispersion models to calculate pollutant levels is the direct connection to emission inventories and projections.

New functionality, parameterizations and inputs have been developed with the goal of increasing the performance of model calculations while preserving storage capacity. This is crucial to be able to carry out a comprehensive national modelling with a high geographical resolution. Parameterizations and detailed input data have been developed to better represent the real dispersion conditions, the physical environment and the size of emissions from, for example, traffic.

For NO_2, high levels are seen in urban environments near roads with high traffic load, and exceedances of the air quality limit values are seen in several locations. The number of exceedances of current air quality standards are relatively low for PM10. Levels of PM2.5 are often low and no exceedances of current standards occur at all. In a future perspective with stricter requirements for clean air, the situation will likely be different. With potentially stricter limit values there is a risk for exceedances in the several Swedish municipalities, especially for PM10.

The validation of the modelling results compared to measurements has shown that modelling quality objectives are achieved for PM2.5 at both urban and local traffic stations. For NO_2 and PM10, the modelling quality objectives are not met. The model underperforms at a number of stations and the 90 % requirement is thus not achieved. The RDE indicator is however fulfilled for several stations except for NO2 at traffic stations where the margin to fulfilment was very close. Further investigation of these sites is required and should be prioritized to understand the causes and improve modelled concentrations. Model performance, memory and storage capacity remain a major challenge for performing high-resolution calculations efficiently. Work on this also needs to be prioritised in future projects.

The national modelling results constitute a national description of the current state of air quality in which all of Sweden's municipalities are included. The dataset facilitates the identification of locations where air pollution levels are at risk of exceeding threshold values for air quality standards and environmental quality objectives. This can be of great help to municipalities that lack measurements and modelling of air pollution and supports the work with Swedish air pollution assessment and mitigation. A comprehensive national assessment is especially important to have available when the updated EU Ambient Air Quality Directive, with stricter requirements for clean air, is implemented in the coming years. The dataset can also support the design of measurement networks, selection of measurement site locations and provide valuable information to experts and researchers as well as an interested public. The results will be made freely available on the SMHI web portal “Luftwebb” by the turn of the year 2023/2024.

Sammanfattning

I detta utvecklingsprojekt har halter av NO_2, PM10 och PM2.5 beräknats för hela Sverige för år 2019. Simuleringar har gjorts med en ny metodik som möjliggör en nästan helt sömlös kombination av spridningsmodellering på tre skalor; regional, urban och gaturum, utan att dubbelräkna emissioner. Föroreningshalter har beräknats på 50x50 m^2 upplösning, vilket ger ett komplett och detaljerat dataset på nationell nivå. Den spatiala upplösningen på 50 m fångar koncentrationsgradienter av vikt för högupplösta exponeringsberäkningar. En styrka med att använda spridningsmodeller för att beräkna föroreningshalter är den direkta kopplingen till emissionsinventeringar och projektioner.

Ny funktionalitet, parametriseringar och indata har tagits fram med målet att öka prestanda och kvalitet för modellberäkningar samtidigt som lagringskapacitet bevaras. Detta är avgörande för att kunna genomföra en heltäckande nationell modellering med hög geografisk upplösning. Parametriseringar och detaljerade indata har tagits fram för att bättre representera de verkliga spridningsförhållandena, den fysiska miljön samt storlek på utsläpp från exempelvis trafik.

För NO_2 ses höga halter i urbana miljöer nära trafikbelastade vägar med överskridanden av gränsvärden för olika normer på ett flertal platser. Antal överskridanden av nuvarande miljökvalitetsnormer är förhållandevis få för PM10. Halter av PM2.5 är ofta låga och inga överskridanden av gällande normer sker alls enligt modellresultaten. I ett framtida perspektiv med högre krav på ren luft blir troligtvis situationen en annan, där striktare gränsvärden riskerar att överskridas i flera svenska kommuner, speciellt för PM10.

Valideringen av modellresultat gentemot mätningar har visat att modelleringskvalitetskraven uppnås för PM2.5 vid både urbana och trafiknära platser. För NO_2 och PM10 uppnås inte modelleringskvalitetskravet för 90 % av mätstationerna då modellen underpresterar vid ett antal platser. RDE indikatorn för modellkvalitet uppfylls dock för flertalet stationer förutom för NO_2 vid trafiknära stationer, där marginalen dock är liten. Vidare undersökning av dessa platser krävs och bör prioriteras för att förstå och förbättra modellerade halter i framtida projekt. Modellprestanda, minnes- och lagringskapacitet är fortsatt en stor utmaning för att genomföra högupplösta beräkningar på ett effektivt sätt. Arbetet med detta behöver också prioriteras framöver.

Dessa nationella modelleringsresultat utgör en nationell nulägesbeskrivning av luftkvaliteten där alla Sveriges kommuner ingår. Datasetet underlättar identifiering av platser där luftföroreningshalter riskerar att överskrida tröskelvärden för miljökvalitetsnormer och miljömål. Detta kan vara till stor hjälp för kommuner som saknar mätningar och modellering av luftföroreningar och gynnar arbetet med svensk luftvård. En heltäckande nationell kartläggning blir speciellt viktigt att ha till förfogande när EU:s uppdaterade luftkvalitetsdirektiv, med striktare krav på ren luft, införlivas de kommande åren. Det nationella modelleringsunderlaget kan också utgöra stöd vid mätnätverksdesign, val av mätplats och ge värdefull information till experter och forskare såväl som en intresserad allmänhet. Resultaten kommer att tillgängliggöras fritt på SMHI:s webbportal Luftwebb till årsskiftet 2023/2024.

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1 Background

In 2021, the World Health Organization (WHO) presented new updated air quality guidelines that provide clear evidence that air pollution affects health at lower concentrations than previously understood. These guidelines were used as the basis for the proposal for a revised air quality directive with stricter air quality limits presented by the EU Commission in October 2022. Negotiations for the proposal are ongoing during 2023. The European Parliament and the European Council have adopted their respective negotiating positions on a revised directive and the so-called trilogues were commenced in November 2023 in order to reach agreement on a final revised text of the directive. The proposal is to set air quality standards that are closer to the WHO guidelines, and would be legally binding by 2030. Some key changes are stricter limit values for annual mean concentrations of PM2.5 (new limit at 10 µg/m^3, down from 25 µg/m^3), NO_2 and PM10 (new annual limit at 20 µg/m^3, down from 40 µg/m^3). Furthermore, the European Parliament has called for a full alignment with WHO air quality guidelines by 2035.

There are two means in which air policies facilitate reduced exposure to air pollution, by regulating the level of pollution in the outdoor air and also by regulating emission amounts. All EU member states have national emission reduction commitments until 2030 for air pollutants through the NEC directive. Member states shall produce and implement national air pollution control programs which have to be updated at a minimum every fourth year as a tool to reach their reduction commitments. Sweden reported its first national air pollution control program to the EU in April 2019, and according to the national emission inventory and scenarios for air pollutants, Sweden needs to implement policies and measures to further reduce emissions of NO_x and ammonia to reach the national reduction target for 2030. The control program contains two action areas for the reduction of emissions of NO_x and ammonia. The action area focusing on NO_x emissions include industry and district heating, and the other focusing on ammonia include emissions from transport. Sweden plans to report an updated version of the national air pollution control program to the EU by the end of 2023.

Air quality in Sweden has improved over the past decades due to reduced emissions from several source sectors. Current limit values for air quality are however still being exceeded in some urban areas. With more stringent air quality standards it is likely that limit values will be exceeded more often and may also become more frequent not only in larger cities but also in smaller towns. It is thus expected that effort to further reduce air pollution levels is needed.

Air quality monitoring is generally common in larger Swedish cities but less frequent in smaller towns. A nationwide dataset that describes air pollution levels locally in all Swedish municipalities does not exist and is important information to have access to before the revised EU Ambient Air Quality Directive has been implemented. National quantifications of air pollution levels based on air quality modelling can thus be useful and SMHI has developed a new dispersion modelling approach, based on the regional model MATCH and the CLAIR platform, which allows for national air quality assessments with high quality and high resolution. These assessments provide improved data for health studies and cost analyses. Dispersion results can be further used for assessing the potential of needed actions in the Swedish National Air Pollution Control Program, as well as supporting local action plans and evaluating the progress towards achievement of the Swedish environmental quality objectives. Further it will support the national efforts for air quality abatement to ensure compliance with the more stringent limit values in the upcoming revised EU Ambient Air Quality Directive.

2 Aim

The aim of the project was to carry out dispersion modelling at high resolution of NO_2, $PM_{2.5}$ and PM_{10} for the year of 2019 covering Sweden. The total concentrations of the included compounds should be described through three contributions; regional, urban and street canyon.

The project included development of methodology and functionality with the objective to improve simulated air pollution levels through updated parameterizations, input data and new functionality for increasing the efficiency and performance of run time calculations while also limiting data storage.

The year of 2019 was used as a baseline to avoid effects of the Covid-19 pandemic on the air quality.

The results from this study will be useful data when assessing current and future stricter limit values for air quality and the progress towards achievement of the Swedish environmental objectives for clean air.

3 Methodology

Calculations in this study follow a dispersion modelling chain, where dispersion models are used on different geographical scales, together with input data such as emissions, meteorology, physiography and a building database. Figure 1 gives a schematic overview of how the modelling chain is carried out in order to calculate air pollution levels on high resolution for all of Sweden.

All steps along the modelling chain are described below, from input data and emission preparation to dispersion modelling on regional, urban and local scale. Emission and dispersion calculations are done hour-by-hour for the year 2019. The air pollution concentrations calculated using dispersion modelling are adjusted using observations, both on a regional and urban scale.

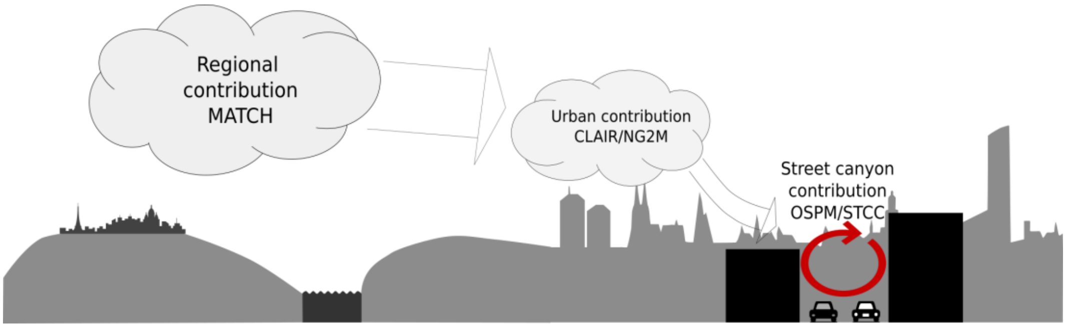

Figure 1. Parts involved in the calculation of air pollution levels down to street canyon for all of Sweden.

3.1 Emission data

Dispersion models require emissions as input data. Gridded emissions (1x1 km^2 resolution) within Sweden have been prepared by SMED[1] for 2019.

Emissions from the rest of Europe are based on EMEP emissions[2] (0.1 degree resolution). Emissions from forest fires are also included in the European model calculation, in the form of daily data from CAMS Global Fire Assimilation System (CAMS-GFAS).

3.1.1 Further improved urban emissions

In order to allow higher spatial resolution than 1x1 km^2 for the urban dispersion modelling, the gridded emissions from SMED were improved by using more detailed representations for road traffic, large point-sources and for small-scale residential heating.

High resolution emissions from small-scale residential heating have been attained by a method that combines data from the chimney sweeper registers, building registers and fuel statistics from the Swedish Energy Agency. These emissions are scaled regionally with regional total emissions from SMED in order to fully comply with national statistics.

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[1] Geographically distributed emission data from SMED (emission year 2019): https://www.smhi.se/data/miljo/nationella-emissionsdatabasen

[2] EMEP emission database (emission year 2019): https://www.ceip.at/webdab-emission-database

Road emissions are calculated using the Swedish National Road Database[3], emission factors from HBEFA 4.1[4], together with fleet composition, and traffic flow as described by the air quality system SIMAIR[5] which is an application based on the CLAIR platform (see section 3.4.1). The road database contains traffic data such as annual average daily traffic, the fleet composition and usage of studded tires in different regions in Sweden. An additional improvement was introduced for tunnels, approximating emissions at tunnel entrances and exits by emissions generated inside the tunnel (emissions from the first 300m in the tunnel are moved to the tunnel entrance, in both ends). Hourly exhaust and non-exhaust emissions are calculated for each road.

The non-exhaust emissions from traffic are modelled using the emission model NORTRIP[6], which has recently been integrated into the CLAIR platform. This model is used to calculate non-exhaust emissions hour-by-hour and considers meteorological conditions such as humidity, precipitation, temperature etc in order to estimate direct emissions to the air, as well as emissions that are retained temporarily on the road, forming a dust layer that may be re-suspended later. The most important processes generating non-exhaust emissions from road traffic are road, brake and tyre wear. Where sanding is used during winter time, this constitutes an additional source. The size-distributions for PM generated by these different processes are prescribed in the NORTRIP model configuration (for the calculations in this project, the default size-distributions are used with the addition of allowing crushing of large particles to smaller fractions and activating sand as gritting method of winter roads). When all different processes represented in NORTRIP are considered the fraction of PM2.5 in relation to PM10 is approximately 8%. This is a lower fraction than has been assumed in previous studies, resulting in lower emissions of non-exhaust PM2.5 in this study in comparison to other studies (e.g. Segersson et al. 2017). Also, since emission calculations were performed for individual roads in parallel with the dispersion modelling, no total national emission for non-exhaust emissions is presented.

In the diagrams in Figure 2 Swedish emissions are presented for 2019. The different emission sectors are defined according to the GNFR activity categories[7] which are presented in Table 1. Note that non-exhaust traffic emissions are not included in the diagrams, because emissions are calculated dynamically within the dispersion modelling calculations.

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[3] Swedish National Road Database: https://www.nvdb.se/sv/about-nvdb/

[4] HBEFA: https://www.hbefa.net/e/index.html

[5] Technical documentation of SIMAIR: https://www.smhi.se/forskning/forskningsenheter/luftmiljo/simair-teknisk-beskrivning-1.602

[6] NORTRIP: https://www.nilu.no/wp-content/uploads/dnn/23-2012-BDE-IS_NORTRIP-model-description.pdf

[7] GNFR activity codes: https://www.ceip.at/fileadmin/inhalte/ceip/1_reporting_guidelines2014/annex_i_rev18-11.xlsx

Table 1. GNFR emission sectors and descriptions.

GNFR	Description
A: PublicPower	Emissions from public electricity and heat production
B: Industry	Emissions from industrial combustion plants
C: OtherStationaryComb	Emissions from small combustion plants
D: Fugitive	Fugitive emissions
E: Solvents	Emissions from the use of solvents
F: RoadTransport	Emissions from road transport
G: Shipping	Emissions from domestic shipping
H: Aviation	Emissions from landing and take-off, for domestic and international flights
I: Offroad	Emissions from offroad mobility, such as machinery used in industry, households, agriculture, railways and fishing
J: Waste	Emissions associated with waste handling (except combustion for energy)
K: AgriLivestock	Emissions associated with livestock and manure management
L: AgriOther	All other agricultural emissions, such as fertilizer, crops and field management
M: Other	Other anthropogenic sources
N: Natural	Emissions from natural sources, such as forest fires
O: AviCruise	Emissions from the cruise phase of both domestic and international flights
P: IntShipping	Emissions from international shipping
z_Memo	Multilateral operations

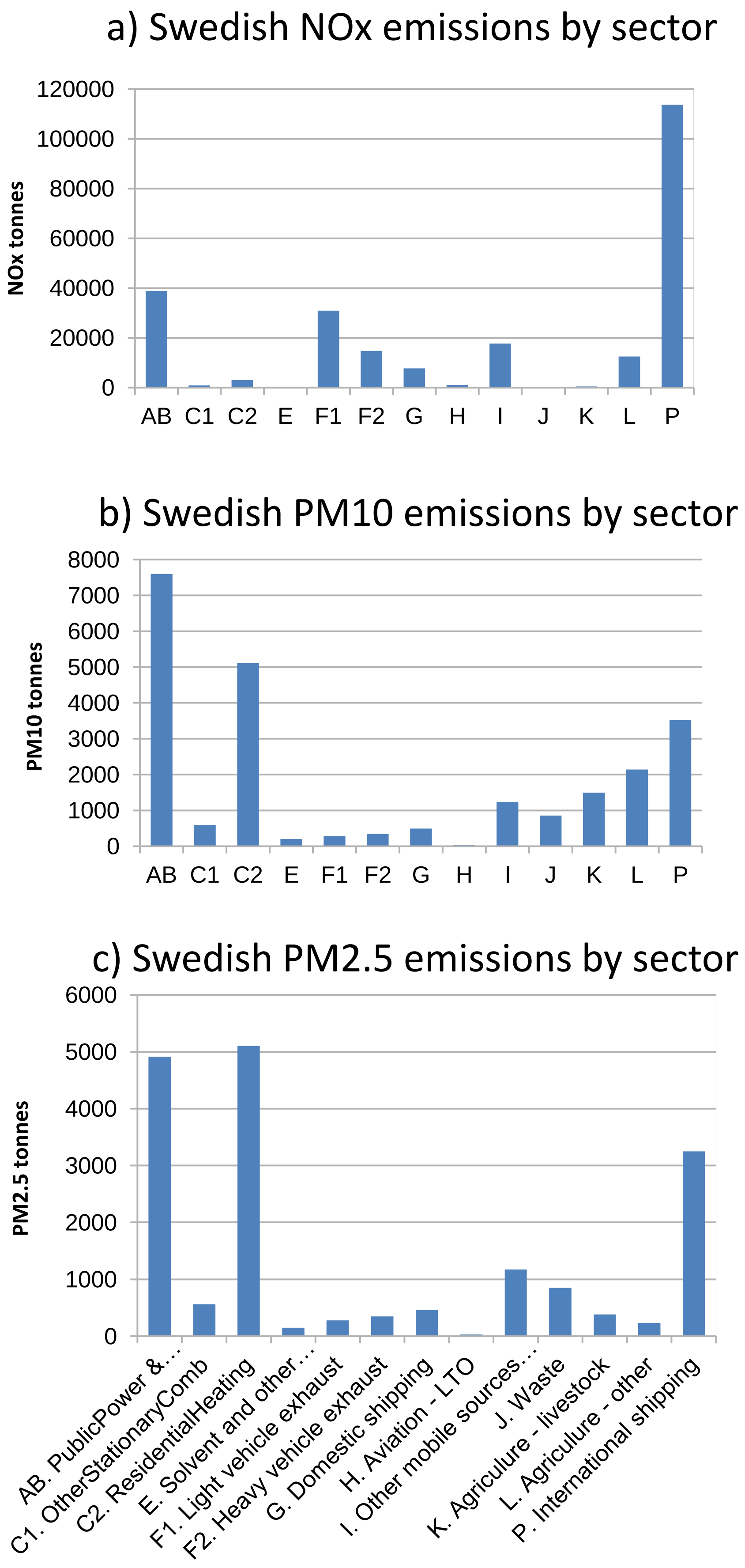

Figure 2. Swedish emissions by sector for 2019 for a) NO_x, b) PM10 and c) PM2.5.

3.2 Updated input data

3.2.1 Buildings

The ventilation within street canyons is strongly linked to the surrounding building geometry and wind flow (direction and speed). These in turn have a strong effect on air pollution dispersion. For model simulations within street canyons it is important to have accurate data which can describe important physical parameters in these types of environments. Oftentimes data from Open Street Map (OSM) is insufficient in describing the building height, but it is used in SIMAIR/CLAIR due to limitations in commercial use for other data sources. Therefore geographic building data obtained from OSM as polygons were combined with building height data obtained from laser data (”Laserdata skog”) produced by the Land Survey (Lantmäteriet). This is an open, nationwide dataset which covers the height of land surface objects (e.g. buildings, masts, trees etc.). For every building within a polygon each building height was sampled and the 90-th percentile chosen as the actual height of the building polygon. This percentile was chosen to avoid including objects which have no influence on the air ventilation within a street canyon, such as chimneys or masts. An example of resulting building heights together with point data from laser scanning is shown in Figure 3.

Buildings with a surface area less than 40 m^2 and/or height less than 2 m were excluded from the data. For areas where there is no data from Laserdata skog published, building heights have been estimated based on either the height in the Openstreetmap database, or the number of building levels combined with the building type. This mainly affects the region in and around Örebro.

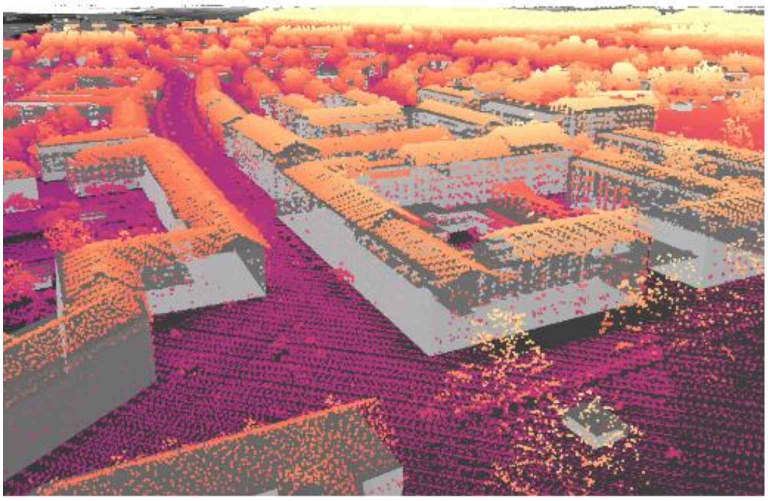

Figure 3. An example of building heights in a neighbourhood, together with point data from laser scanning.

3.2.2 Congestion profiles in urban areas

Emission factors may be strongly affected by traffic intensity or congestion. In HBEFA this is represented through different emission factors depending on the ”level of service” (1-5, representing free-flow to heavy stop+go). Traffic flows for several cities have been studied using traffic information services from open web application services (trafiken.nu and Google maps). Several roads in central parts of Swedish cities show an indication of some level of congestion, especially during the morning and afternoon rush. Congestion profiles have been defined that represent the variation in level-of-service hour-by-hour over a typical week. The profiles represent a conservative estimate, only adjusting the level-of-service during morning rush hours 7-9 and late afternoon 16-18. Also, the congestion profiles at most increase the level-of-service to level 2, reflecting slow moving traffic. 12 cities were selected in total (Table 2) mainly based on the population. Skellefteå, Örnsköldsvik and Umeå were also included due to relatively high NO2 levels during the year 2019.

Table 2. Congestion profiles for different cities in Sweden, the name signifies level of service and times for which they are valid. Slow in this case corresponds to Level of service 2 in HBEFA 4.1. All other hours of the day are assumed to be free flow, meaning no congestion.

City	Congestion profile
Stockholm	Slow 7-9, 16-18
Göteborg	Slow 7-9, 16-18
Malmö	Slow 7-9, 16-18
Helsingborg	Slow 7-9, 16-18
Jönköping	Slow 7-9, 16-18
Linköping	Slow 7-9, 16-18
Örebro	Slow 7-9, 16-18
Västerås	Slow 7-9, 16-18
Uppsala	Slow 7-9, 16-18
Skellefteå	Slow 15-17
Örnsköldsvik	Slow 7-9, 16-18
Umeå	Slow 7-9, 16-18

Only major roads were included (functional road type 1-6), see Figure 4 for examples for Stockholm and Göteborg. The inclusion of congestion profiles is expected to increase the emissions from road traffic and further improve the time-variation of the traffic emissions. In the future, more levels of congestion may be included than have been applied in this study. Further analysis would have to be carried out to study typical traffic flow patterns in greater detail which is a time-consuming task. In this pilot study the focus has been to describe congestion on a general level that may be applied to several cities.

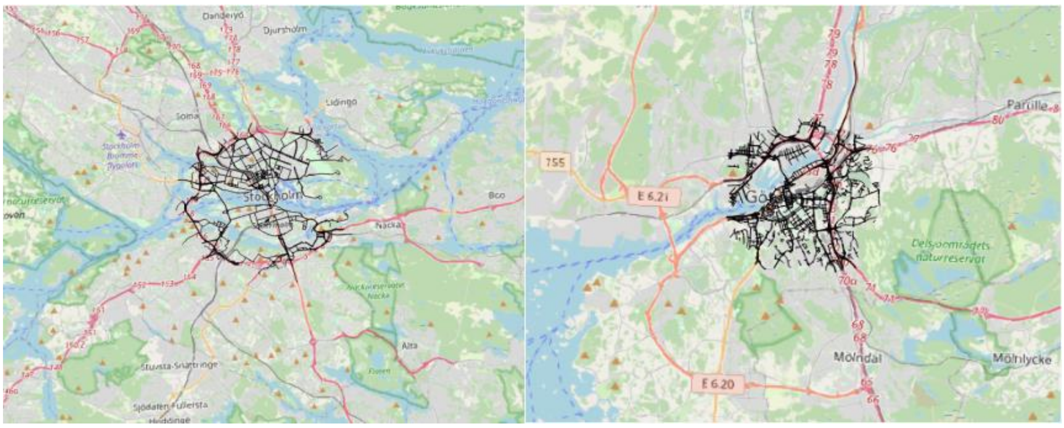

Figure 4. The major roads in central Stockholm and Göteborg, where congestion profiles are applied in this project. Background map: Openstreetmap contributors.

3.2.3 Studded tyre use in cities

The use of studded tyres during the winter season is a large generator of road wear particles, giving rise to very high PM10 levels during dry episodes in the spring. Every year the Swedish Transport administration quantifies the share of vehicles with studded tyres[8] There is data available both regarding six regional areas and a number of cities. The data shows that in southern Sweden the use of studded tires is lower in some urban areas when compared to the larger region (Figure 5). 18 urban areas have been included in this project in addition to the regional areas, in order to better describe emissions from road wear.

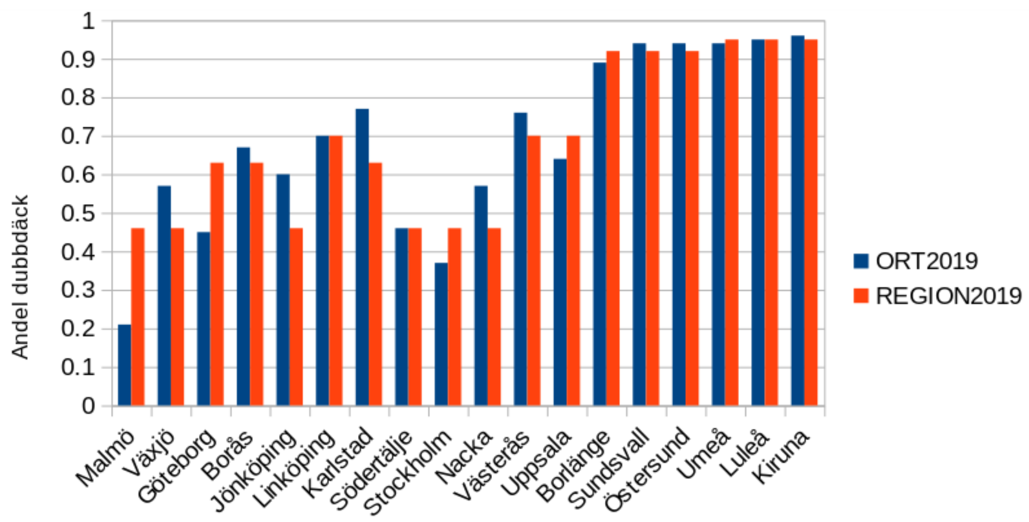

Figure 5. Improved data of use of studded tyres is used for 18 cities.

3.3 Meteorological data

Gridded meteorological data for year 2019 has been used for the modelling. In the MATCH model, 3-dimensional meteorological data for all of Europe is needed and data from the ECMWF weather model HRES[9] (0.1 degree horizontal resolution) is used. For the urban dispersion modelling, hourly weather data from MESAN[10] (2.5 km resolution) is used, together with global radiation from STRÅNG[11].

The meteorology varies from one year to the next, which can cause variations in air pollution concentrations and in e.g. precipitation. Generally, cold and stable weather tends to create atmospheric conditions which promote high air pollution levels while wet and windy weather tend to have a decreasing effect on air pollution levels.

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[8] Trafikverket: Undersökning av däcktyp i Sverige vintern 2019: http://trafikverket.diva-portal.org/smash/get/diva2:1357111/FULLTEXT01.pdf

[9] HRES meteorological data: https://confluence.ecmwf.int/display/FUG/HRES+-+High-Resolution+Forecast

[10] MESAN meteorological data: https://www.smhi.se/data/utforskaren-oppna-data/meteorologisk-analysmodell-mesan-arome-api

[11] STRÅNG global radiation data: https://www.smhi.se/forskning/forskningsenheter/atmosfarisk-fjarranalys/strang-en-modell-for-solstralning-1.329

Emissions from natural sources vary with the meteorology but the anthropogenic emissions usually vary less between each year.

The year of 2019 was a warm and wet year[12] compared to the 30-year period of 1961-1990, which is the standard normal period decided by the World Meteorological Organization. The warm weather, not only in Sweden but in all of Europe, has effects on for example ozone and particulate matter. Warm and sunny weather in the summer months increases ozone production. Warm weather in the winter months decreases the amount of PM emissions from small-scale heating, thus also likely has a reducing effect on the concentration levels of particles.

In Figure 6 the temperature and precipitation deviation of 2019 from the normal period is shown for Sweden.

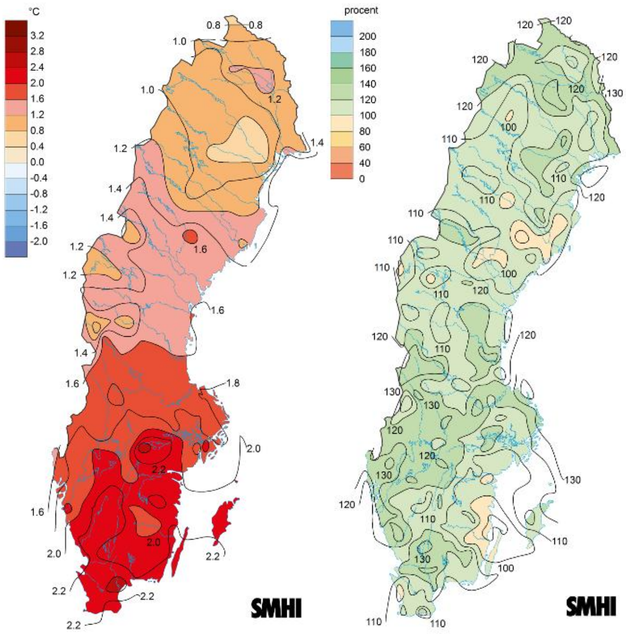

Figure 6. Annual mean deviations in temperature (˚C) and precipitation (percent) from the normal annual mean (mean value of 1961-1990) for 2019.

3.4 Dispersion calculations

3.4.1 The CLAIR platform

The CLAIR air quality modelling toolbox, developed by SMHI since 2017, has been used for the urban scale modelling. CLAIR integrates urban and local dispersion models with emission inventories, emission models and monitoring data, and provides an automated modelling chain. Performance critical parts of the computations can be executed in parallel on a remote cluster.

CLAIR includes tools to perform modelling using a tiled approach, where urban scale dispersion modelling is performed for multiple small areas (10x10 km^2 in this project) and then aggregated to produce a complete dataset (Segersson et al., 2021). This allows

[12] SMHI: https://www.smhi.se/klimat/2.1199/aret-2019-varmt-och-blott-1.154497

for very high-resolution model results across large geographical areas, in this case the whole of Sweden.

The modelling toolbox has undergone thorough evaluations and has been applied for multi-year exposure simulations regionally and nationally for Sweden aimed at developing new dose-response functions for health impact assessment. CLAIR also serves as a core component for a range of on-going research projects and air quality services currently provided at SMHI.

3.4.2 The modelling concept

A combination of dispersion modelling at regional, urban and street level scale has been used, where transport over longer distances than around 15 km is described by the regional dispersion model MATCH (Multi-scale Atmospheric Transport and CHemistry model) (Robertson et al., 1999; Andersson et al., 2007; Andersson et al., 2014) and transport at shorter distances is described using the Gaussian model NG2M which is run on the CLAIR platform. At street level the street canyon model OSPM has been used. Each model is tailored to capture the most important processes at the spatial and temporal scale for which they are applied.

In order to avoid double-counting of contributions from emission sources when adding concentrations from the regional and the urban dispersion model, the contribution from local sources is first removed from the regional concentration fields. This is handled by a post-processing scheme named BUDD (Backtrace Upwind Diffuse Downwind). BUDD follows a trajectory upstream to find the concentration unaffected by nearby emissions. A vertical profile at the upstream location is then allowed to diffuse while traveling downstream, ensuring that high-level emissions at the upstream location are not neglected.

The full modelling concept using MATCH, BUDD and NG2M is further described in Segersson et al. (2021).

Concentrations within street canyons are calculated using the Operational Street Pollution Model (OSPM). The street canyon contribution (STCC), i.e. the concentration increment due to reduced ventilation in the street canyon, is calculated by subtracting two OSPM simulations, one including the effect of buildings and a second simulation where buildings have been excluded.

In Figure 7 the concept is presented in a schematic diagram.

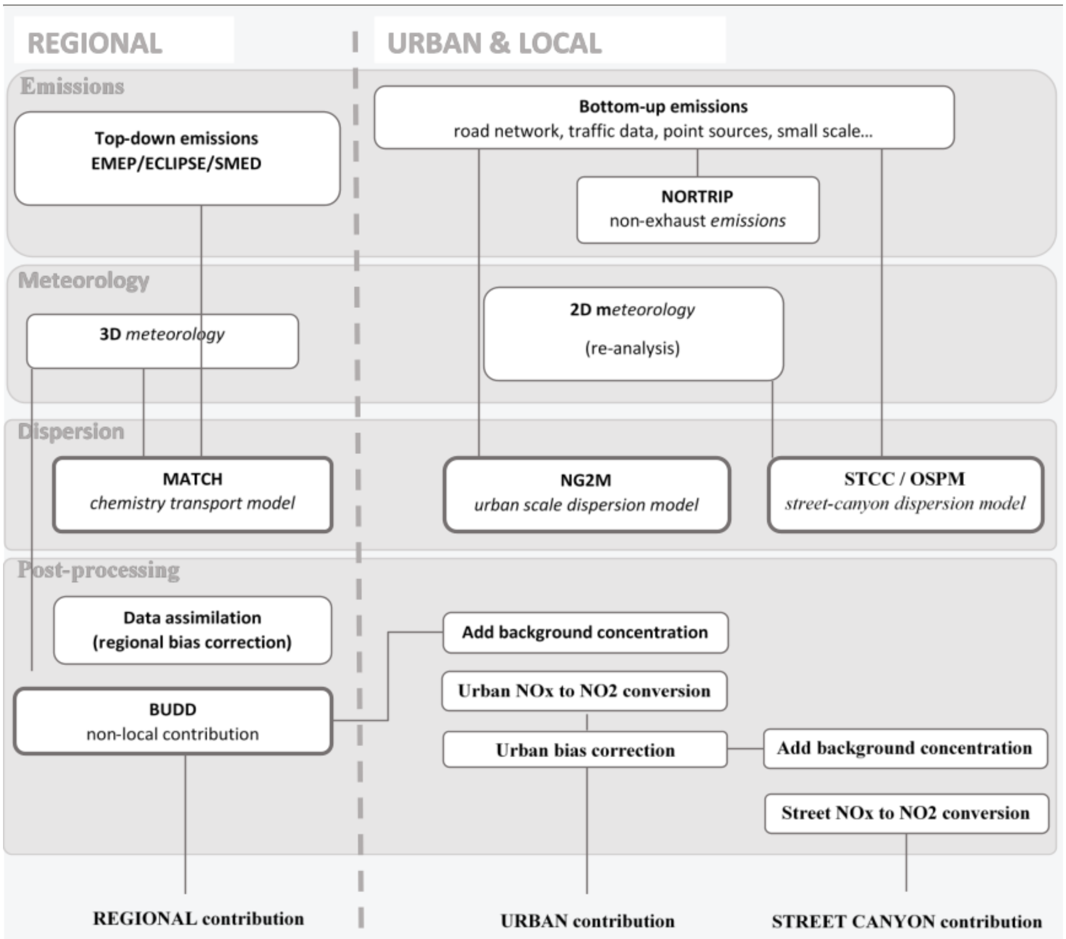

Figure 7. Schematic illustration of the modelling concept used in this study. The modelling consists of three main model chains (columns) for calculating the regional, urban and street canyon contribution which make up the total air pollution concentration. There are several data flows from input data (emissions and meteorology) into the dispersion models (MATCH, NG2M and STCC/OSPM) followed by a number of consecutive steps for post-processing of data (such as bias corrections, NO2-NOx-O3-chemistry). All steps within the CLAIR-system (urban and local) are automated.

3.4.3 Regional scale dispersion calculations

The chemical transport model MATCH is used to calculate the regional concentration levels at a 5 km horizontal resolution. A model run is first carried out for all of Europe on 0.1 degree resolution (approximately 11 km). A nested model approach is used to further increase spatial resolution over Sweden to 5 km. Results from the coarser model run is used as boundary conditions. This method allows for MATCH to capture contributions from the entire European continent, and have higher resolution over Sweden, despite very heavy MATCH calculations on a supercomputing cluster at the National Supercomputer Centre (NSC) in Linköping.

Emissions from forest fires are included in the European model calculation, in the form of daily data from CAMS Global Fire Assimilation System (CAMS-GFAS). Sea salt contribution to particulate matter is also included in the MATCH calculation.

There are particle emission sources that are diffuse and difficult to describe; for example dust from agriculture, pollen and other natural sources; which are partly or totally missing in the emission data used in this modelling. In order to avoid systematic underestimation of modelled particle levels, a bias-correction is carried out using hourly/daily regional measurement data for 2019. The daily bias is calculated at the location of each regional background measurement site, and an interpolation is then carried out hour by hour over Sweden, where the delta is used to adjust the modelled concentration fields.

A similar approach is used for regional measurements of NO_2 and O_3, in order to create the most accurate regional background concentrations for 2019.

Finally, the post-processing scheme named BUDD (Backtrace Upwind Diffuse Downwind) is applied to the regional concentrations in order to not double count contributions from urban sources.

3.4.4 Urban scale dispersion modelling

An urban contribution to the pollution concentration levels has been calculated using the Gaussian dispersion model NG2M.

In order to efficiently run the NG2M dispersion model, the national domain is divided into sub-domains here called tiles. Each tile is 10x10 km large and corresponds to a model run. For each tile, emission sources within the tile and an emission buffer zone are included in the simulation. The horizontal resolution is 50 meters, which means that each tile contains 200 x 200 = 40000 receptor points.

Within the national domain, the urban scale dispersion modelling has been limited to all (10x10 km^2) tiles where at least one person lives, leading to 3738 tiles in total, which in turn means that concentrations have been calculated at almost 150 million receptor points. For the tiles where there is no population, the regional scale modelling results have been used instead, in order to obtain a full result.

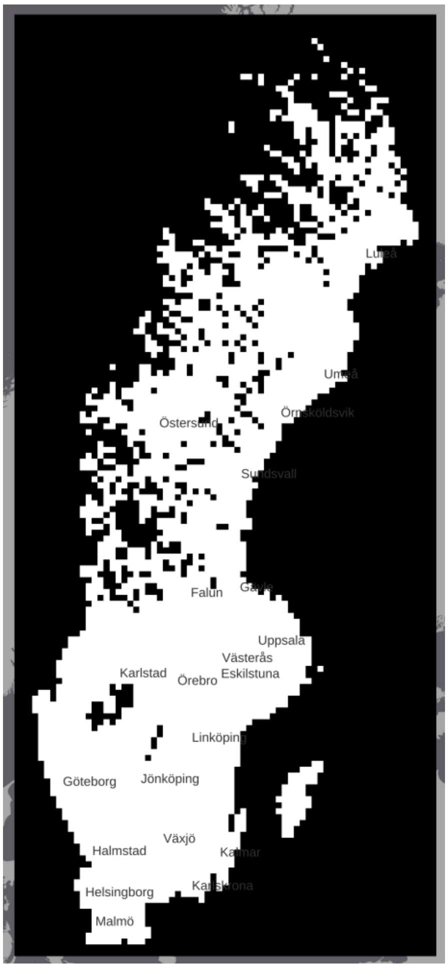

Figure 8. The tiles (sub-domains) where urban scale dispersion modelling has been carried out can be seen in the map as white cells. For black cells, no urban-scale modelling is run and the concentrations are only described using the regional scale dispersion model.

The dispersion simulations are run hour-by-hour, using hourly meteorological input, hourly emission data and also hourly data for regional background concentrations.

To provide a source apportionment, five emission sectors are handled separately in the NG2M model. The following sectors have been used in the project (see Table 1 for information on GNFR sectors):

- Traffic exhaust: GNFR sector F (excluding tyre and brake wear, road abrasion)
- Traffic non-exhaust: non-exhaust calculated using NORTRIP
- Small-scale residential heating: GNFR sector C2
- Shipping: GNFR sectors G, P
- Other sources: GNFR sectors A, B, C1, E, H, I, J, K, L

Emissions can be described using four different source types in CLAIR; point, line, area and grid sources. Different plume formulations are used in NG2M for the different source types. Grid sources are interpreted as multiple area-sources in NG2M. Traffic sources are represented by line sources for each road segment and small-scale heating are gridded sources at 100 m resolution. Shipping emissions are also treated as gridded emission sources, while the “other sources” sector contains a mixture of gridded emissions and discrete point sources for large industrial facilities. The NG2M model handles point sources by including effects of plume-rise and downdraft. Gridded emissions are distributed vertically to reflect typical release heights for each sector.

While the CLAIR system runs on a server at SMHI, the NG2M dispersion model is executed remotely on a supercomputing cluster at the National Supercomputer Centre (NSC) in Linköping. Multiple tiles are run in parallel, and within each tile the NG2M model is parallelized in time and for substances, allowing for all pollutants to be modelled in the same run.

In order to model NO_2, the CLAIR system first models NO_x, then post-processes the hourly NO_x results to obtain NO_2 and O_3, assuming pseudo steady-state (Berkowicz et al., 2011). The post-processing is performed on the same resolution as the NG2M dispersion model results and the regional background is interpolated to match the local grid.

As a final step in the simulation in each tile, relevant statistical metrics are calculated, such as yearly means and percentiles relevant to each substance modelled.

Finally, using hourly urban background measurements, a correction factor is calculated hour-by-hour at each measurement site. Correction factors are interpolated using inverse distance weighting and then gradually dampened with distance from the measurement site. At distances longer than 30 km there is no influence from an urban monitoring station. All available hourly measurements are used to calculated correction factors for PM10, PM2.5 and NO_2. The correction is calculated for the total concentration and applied equally to all source contributions.

A validation of model results compared to urban background measurements is carried out for 2019 and presented in section 4, in order to ensure sufficient model quality.

3.4.5 Street level dispersion modelling

Air pollution levels within street canyons are elevated due to reduced ventilation caused by surrounding buildings. This is not considered in the Gaussian model but requires an additional model. The pollution levels inside the street canyon are calculated using the Operational Street Pollution Model (OSPM), which needs information about building height, street geometry, traffic count, wind speed and a number of other parameters in order to calculate air pollution levels (Bercowitz et al. 1997). Since emissions from the roads inside the street canyon are also included in the urban scale dispersion modelling, adding the results would lead to double counting of the emissions. By instead calculating the increment due to buildings - the street canyon contribution - this is avoided. The street canyon contribution is calculated through subtracting two OSPM simulations, one which includes buildings and a second simulation where buildings have been excluded. The street canyon contribution (C_{STCC} can be expressed with the following equation:

$$C_{STCC} = C_b - C_{nb}$$

Where C_b represents the concentration including the building effect, C_{nb} the concentration without buildings. The STCC contribution is then added to the urban and regional contributions to obtain the total simulated concentration at street level.

To calculate the street canyon contribution for all street canyons nation wide, a new algorithm named STCC has been developed that controls the OSPM simulations and allows for automated localization of canyons in the road network and placement of two receptor points within a street canyon. The algorithm localises a street canyon initially by detecting buildings, followed by roads adjacent to buildings. A receptor point is placed adjacent to buildings on each side of the road. If buildings only exist on one side of the street the two receptor points are placed symmetrically across the street. The average building height is calculated in 12 wind sectors and if several roads are found between the receptor points within the street canyon the traffic load from all roads are included. Another canyon is added when the street canyon configuration changes e.g. building height and/or roads within the canyon. A minimum distance between two adjacent canyons is specified to avoid an excessive number of canyons. Examples of how canyons a are localized are shown in Figure 9.

For roads where the building height is low (height < 3m) or located at a significant distance from the road, the building-effect on air pollution levels is very limited or non-existent. For these roads, no street canyon contribution is calculated.

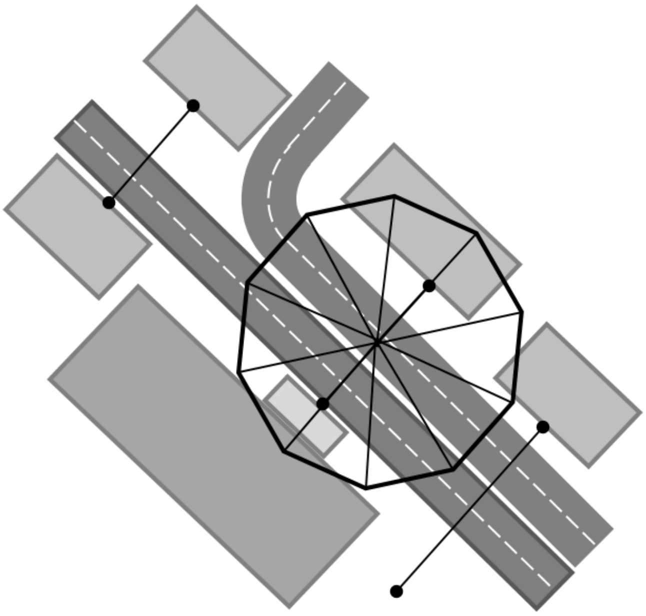

Figure 9. An algorithm called STCC locates canyons along the road network depending on road and building geometries and a number of configurable parameters, such as minimum distance between canyons to be evaluated and minimum distance to a road junction.

3.4.6 Model correction from local traffic sites

In this modelling chain air quality measurements are included both from regional and urban background sites. For these stations correction factors may be assumed to be valid for an area surrounding the stations.

Dealing with measurements from local traffic sites is a lot more complicated. The spatial representativeness of such a site could be as small as a few metres. For example the building height, traffic amounts and street canyon position in relation to the wind direction all have a significant effect on the concentration levels. The pollutants also differ in spatial pattern. This all together makes a general data fusion technique tricky to apply without potentially introducing other unwanted uncertainties.

Since the correction factors for a specific street canyon station are not very transferable, this study have therefore not included corrections of street-canyon results.

A future need is to implement pollutant-dependent techniques to correct or optimise street canyon results with information from measurement stations.

3.5 Functionality and optimisation of model calculations

Apart from optimising the NG2M dispersion model, optimisation has been done for the whole calculation chain: emission calculations, meteorological preprocessing, statistical post-processing of results, NOx-chemistry post-processing, running STCC, reading and writing netCDF and geopackage file formats, database operations and the CLAIR system code itself.

3.5.1 Parallellization methodology

The NG2M model runs multiple substances with low additional computational cost. When the model is used for more than one substance, the model will calculate the dispersion for each source as a unit emission, and scale the resulting concentration field for each substance and the corresponding emission strength. This is done for each time-step and emission source in the simulation.

Apart from the concept of dividing the area to be modelled into tiles, the CLAIR system also parallelizes the dispersion modelling of each tile. Since the NG2M model is a gaussian model, it is very straightforward to parallelize by dividing the simulation in time. Further, the CLAIR system also runs different emission sectors separately. This allows for calculating different sectors at different spatial resolution. Some emission sectors have only coarse resolution and therefore it is not meaningful to calculate the dispersion at very high resolution for those sectors. Once all parts of the dispersion simulation for an individual tile has completed, the CLAIR system puts them together and resamples the parts that have coarser resolution to the highest resolution used.

3.5.2 Refined grid

In order to accurately model the air quality, it is important to capture the concentration gradients. This, in turn, implies running dispersion models at very high resolution, which is computationally expensive. Since the gradient is high close to an emission source but much lower further away, it is possible to speed up a gaussian dispersion model (such as NG2M) by reducing the density of receptor points far away from each emission source.

In this project this has been implemented in the NG2M dispersion model. The ”refined grid” is set up so that as the model calculates the concentration further and further away from an emission source, it skips every second receptor point, while still further away only every third receptor point is included and so on. An example of this may be seen in Figure 10 below.

The resulting dispersion fields are stored at the base resolution and the concentrations at receptor points that have been skipped are interpolated, producing fields that are very close to those obtained when including all receptor points.

The distances when this skipping of receptor points starts may be controlled in the CLAIR system. Extensive testing of this feature allows for saving 40-80 % of the computational effort (for road sources) while maintaining high quality dispersion results.

Figure 10. An example of a refined grid. Close to emission sources receptor points are dense, and further away from the sources there are fewer and fewer receptor points.

4 Results and Discussion

In the following section results for total concentrations, including regional, urban and street canyon contributions, are presented and compared to the air quality standards, air quality objectives and WHO guidelines, presented in Table 3. To visualise results concentration maps are presented both nationally and zoomed in over selected cities. The national maps show total concentrations from regional and urban contributions. Zoomed in maps also contain the street canyon contribution in the form of coloured circles, which allows the viewer to compare levels in street canyons with the urban background levels. It is clear that in some street canyons the total concentration is significantly higher than the background.

Table 3. The concentration levels corresponding to the air quality standards, air quality objectives and WHO guidelines for annual means of NO_2, PM10 and PM2.5 (unit µg/m^3).

Pollutant	NO_2	PM10	PM2.5
Air quality standard[13] (annual mean)	40	40	25
Air quality objective[14] (annual mean)	20	15	10
WHO guideline[15] (annual mean)	10	15	5

4.1 NO_2

The annual mean concentration of NO_2 varies throughout the country. Higher levels can be seen in urban areas around major traffic routes, while rural areas show low levels (Figure 11). Exceedances of the air quality standard of 40 µg/m3, is modelled near several major roads in Stockholm, Göteborg and Malmö. In Norrköping, Falun and Luleå the Swedish air quality objective (20 µg/m^3) is exceeded. Large areas over the three major cities and several more towns (e.g. Helsingborg, Umeå, Luleå, Malmberget, Kiruna) show concentrations above the WHO guideline of 10 µg/m^3. Within street canyons modelled concentration levels are sometimes significantly higher than the urban background. This illustrates the street canyon effect on air pollution levels. The annual air quality standard is exceeded in several street canyons mainly in Göteborg and Stockholm (Figure 12 and 13). Other cities like Malmö, Helsingborg, Norrköping, Uppsala and Falun also show examples of exceedances of the annual air quality standard in street canyons (not shown). Several more street canyons in urban areas in Helsingborg, Malmö and Norrköping reach levels above 32 µg/m^3 (the upper assessment threshold) according to the modelling results.

[13] The Swedish air quality standards: https://www.naturvardsverket.se/globalassets/vagledning/luft-och-klimat/mkn-utomhusluft/sammanstallning-miljokvalitetsnormer.pdf

[14] The Swedish environmental quality objectives for clean air: https://www.naturvardsverket.se/en/environmental-work/environmental-objectives/clean-air/

[15] WHO global air quality guidelines: https://apps.who.int/iris/bitstream/handle/10665/345329/9789240034228-eng.pdf?sequence=1&isAllowed=y

There are several street canyons which have very little or no significant effect on the total concentration. This is apparent for minor roads located outside city centres, where

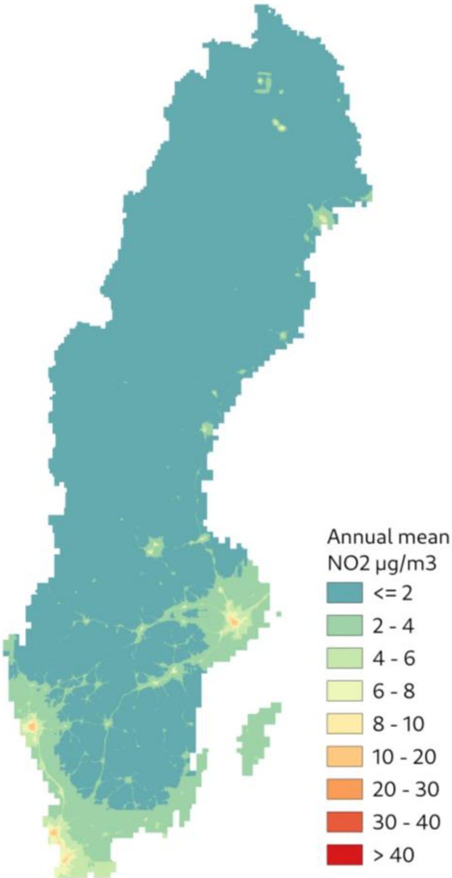

Figure 11. Annual mean concentrations of NO_2 across Sweden 2019. Concentration unit: µg/m^3.

the total concentrations in the street canyon is very similar to the urban background, thus dominated by the urban and regional contribution. As expected in urban environments the urban and street canyon contribution dominate the total annual NO_2 concentrations and a very small contribution originate from regional background. In rural areas levels are usually very low (below 2 µg/m^3).

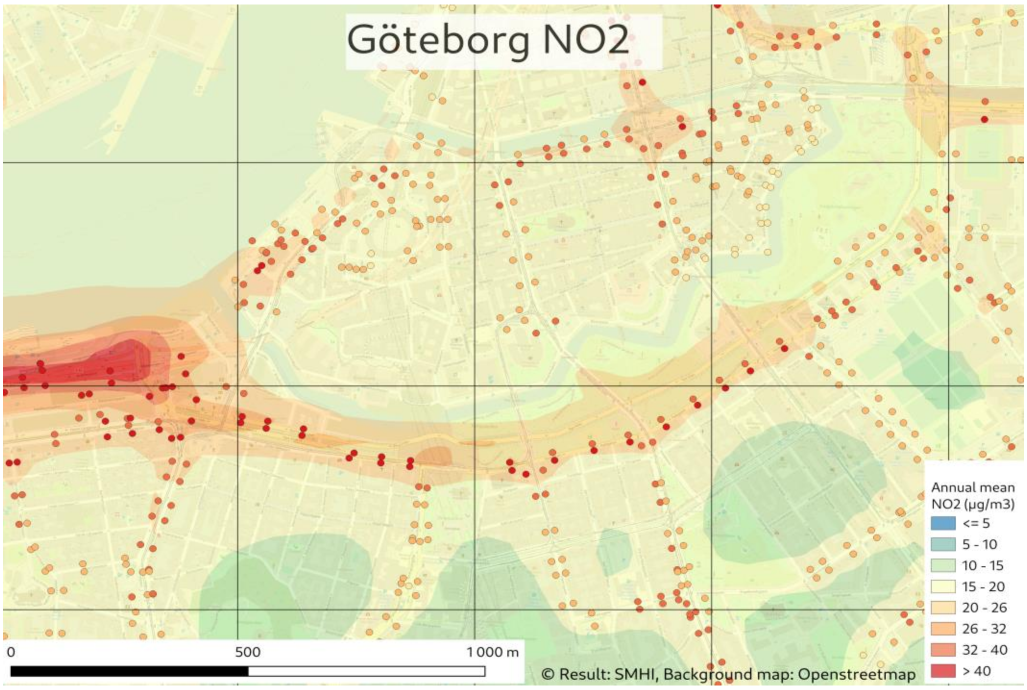

Figure 12. Annual NO_2 concentrations over Göteborg 2019. Circles represent the total concentration from regional, urban and street canyon contributions. Fields represent background concentrations from regional and urban contributions. The concentration intervals in the legend are grouped according to annual threshold values. They are the annual air quality standard (40), upper and lower assessment thresholds (32 and 26), WHO annual guideline (20), and the Swedish air quality objective (10). Concentration unit: µg/m^3.

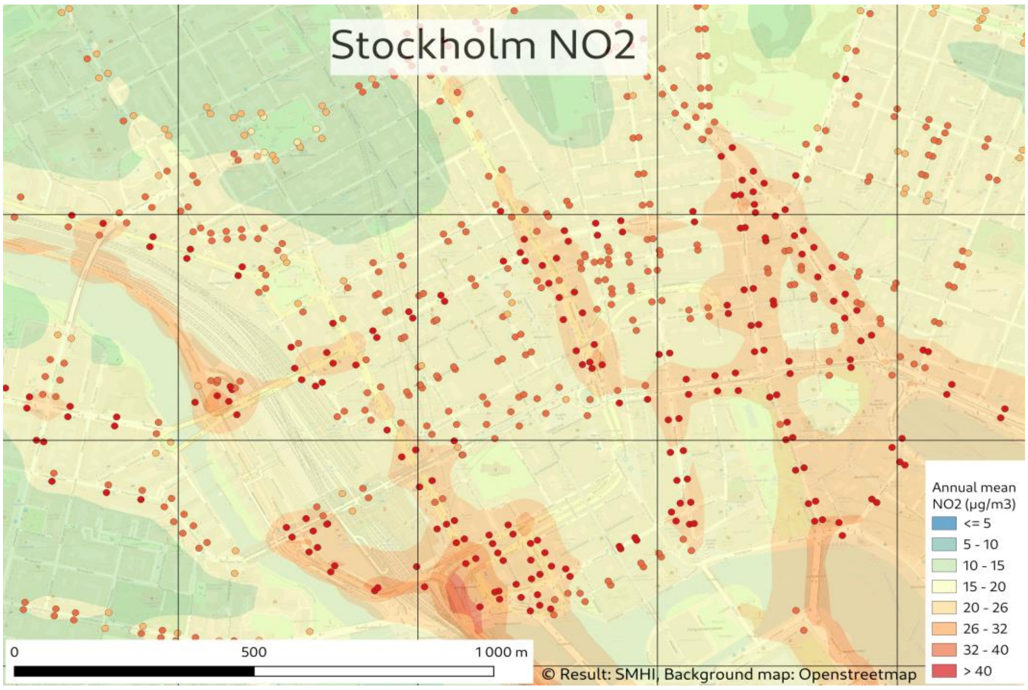

Figure 13. Annual NO_2 concentrations over Stockholm 2019. Circles represent the total concentration from regional, urban and street canyon contributions. Fields represent background concentrations from regional and urban contributions. The concentration intervals in the legend are grouped according to annual threshold values. They are the annual air quality standard (40), upper and lower assessment thresholds (32 and 26), WHO annual guideline (20), and the Swedish air quality objective (10). Concentration unit: µg/m^3.

4.2 PM10

Annual PM10 concentrations are highest in south western Sweden near coastal areas and decrease northward signifying a regional origin of particles partly from the European continent but also from shipping and sea-salt along the coast (Figure 14). In urban areas PM10 levels increase near roads mainly due to non-exhaust traffic-related emissions such as road-wear. There are some grid cells in Stockholm near the motorways E20, E4 and E18 where modelled concentrations exceed the annual air quality standard (40 µg/m^3) in urban background. Several more areas exceed the air quality objective (15 µg/m^3), especially in Stockholm, Göteborg and Malmö and along major motorways both in the southern and northern parts of Sweden.
In street canyons with high traffic load, the building effects can contribute to PM10 concentrations and in a few places the annual air quality standard (40 µg/m^3) is exceeded, mainly seen in Stockholm (Figure 15).

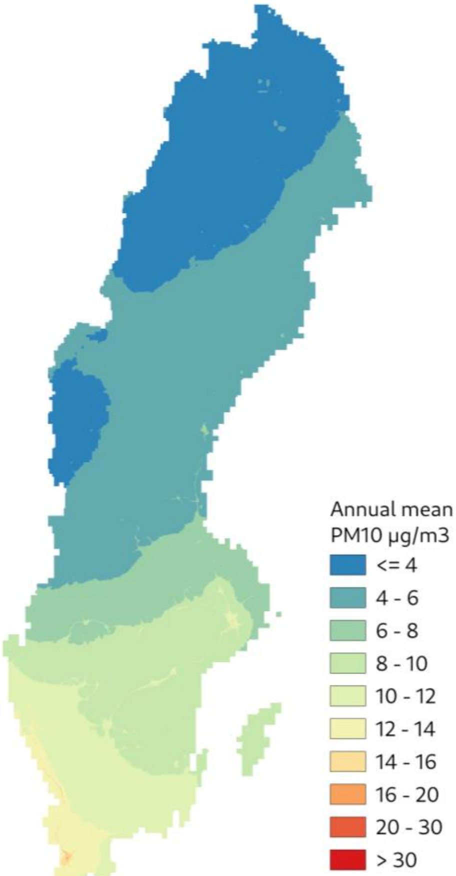

Figure 14. Annual mean concentrations of PM10 across Sweden 2019.
Concentration unit: µg/m^3.

It can be noted that street canyons with less traffic load generally show lower concentrations. High concentrations in urban areas are mainly dominated by the urban contribution near roads and only in a few cases the street canyon contributed to tipping levels above the annual air quality standard. Thus, PM10 levels are dominated by an urban contribution and a regional contribution which is most significant near south western coastal areas. The street canyon contribution is usually the smallest contribution.

A lower limit value for the annual air quality standard for PM10, e.g. 20 µg/m^3 has been suggested in the proposal to the revised EU ambient air quality directive, would result in additional areas in Sweden where the standard could be exceeded. Exceedances of 20 µg/m^3 are commonly seen for long stretches around major roads in and around Göteborg (Figure 16) and Malmö (not shown).

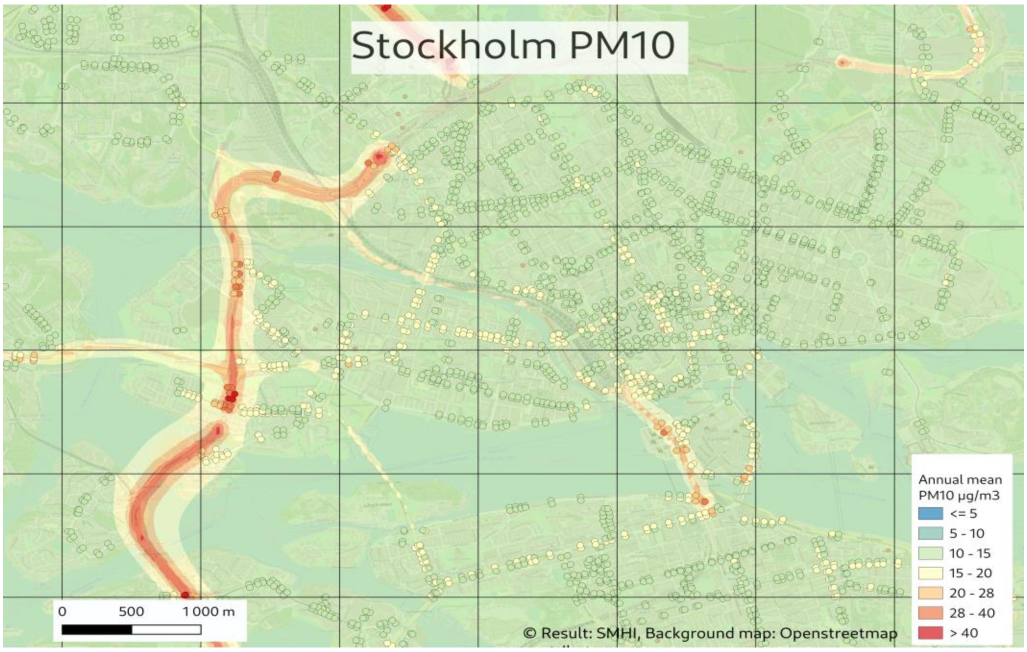

Figure 15. Annual PM10 concentrations over Stockholm 2019. Circles represent the total concentration from regional, urban and street canyon contributions. Fields represent background concentrations from regional and urban contributions. The concentration intervals in the legend are grouped according to annual threshold values. They are; the annual air quality standard (40), upper and lower assessment thresholds (28 and 20), WHO annual guideline (20), and the Swedish air quality objective (15). Concentration unit: µg/m^3.

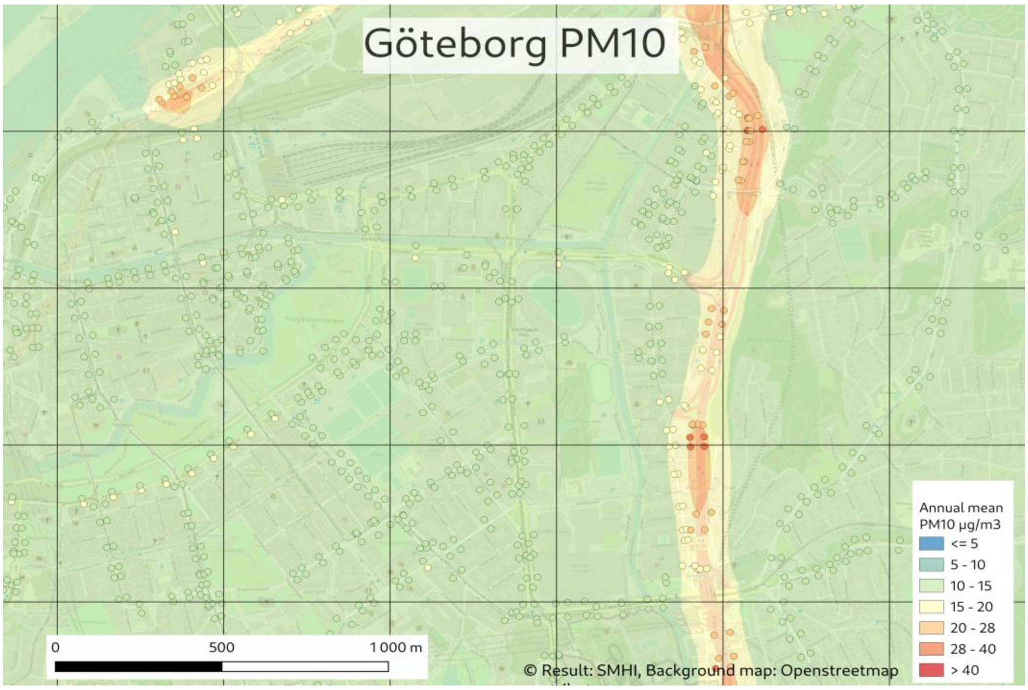

Figure 16. Annual PM10 concentrations over Göteborg 2019. Circles represent the total concentration from regional, urban and street canyon contributions. Fields represent background concentrations from regional and urban contributions. The concentration intervals in the legend are grouped according to annual threshold values. They are the annual air quality standard (40), upper and lower assessment thresholds (28 and 20), WHO annual guideline (20), and the Swedish air quality objective (15). Concentration unit: µg/m^3.

4.3 PM2.5

Concentrations of PM2.5 are relatively low in Sweden and are mainly dominated by a regional contribution from continental Europe as can be seen in Figure 17. The PM2.5 concentrations decrease northward. The highest annual mean concentration levels are found in southern Sweden, with modelled maximum levels around 10-12 µg/m^3.

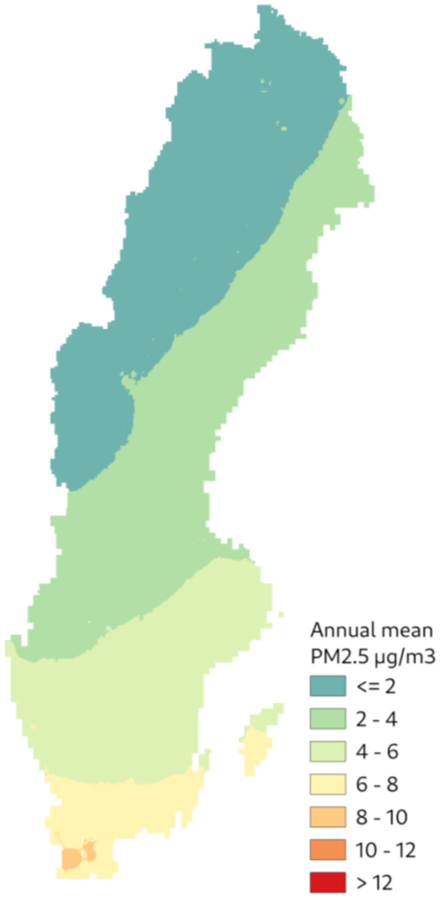

Figure 17. Annual mean concentrations of PM2.5 across Sweden 2019. Concentration unit: µg/m^3.

The annual air quality standard of 25 µg/m^3 is never exceeded according to modelling calculations. The Swedish air quality objective (10 µg/m^3) is however exceeded at several grid cells along the motorway E6/E20 between Malmö and Helsingborg and along major roads within Malmö. There is very little street canyon effect on the annual mean levels, but small contributions can be seen for some street canyons in Malmö (Figure 18).

The air quality guideline from WHO (5 µg/m^3), is exceeded over large parts of Malmö where the background levels vary between 8-10 (orange fields in Figure 18). This is also observed in large parts over southern Sweden, thus work is still necessary to achieve good air quality as recommended by the WHO. The urban contribution is often small and around 20% of the total annual concentration levels and originates to a large degree from non-exhaust traffic sources.

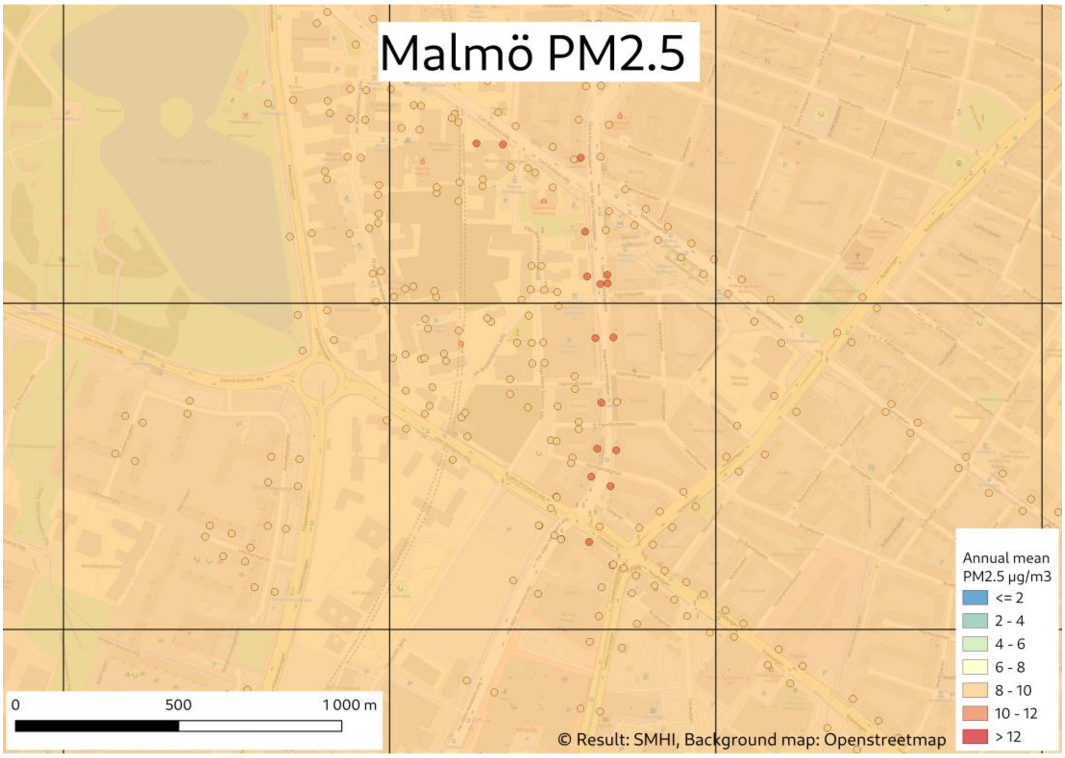

Figure 18. Annual PM2.5 concentrations over Malmö 2019. Circles represent the total concentration from regional, urban and street canyon contributions. Fields represent background concentrations from regional and urban contributions. Concentration unit: µg/m^3.

4.4 Urban background results 2019 compared to scenario 2030

In the exposure study Alpfjord Wylde et al. (2023), air pollution levels are calculated on 250 m resolution for Sweden for the years 2019 and 2030. For 2030 two emission scenarios are used, the “reference scenario” and the more ambitious “alternative scenario”. For particulate matter the two 2030 scenarios show very similar concentrations, but NO2 concentrations are slightly lower in the alternative scenario, especially close to large industrial emission sources.

The resolution of 50 m in this study is 25 times higher than a 250 m resolution, meaning that 25 50 m grid cells fit in a 250 m large cell. Significantly higher resolution allows for much larger gradients close to emission sources. This makes the results from the two studies a bit difficult to compare.

In Alpfjord Wylde et al. (2023), there are very few grid cells with NO_2 concentrations above the air quality objective of 20 µg/m^3 for 2019 and in the 2030 scenarios there are very few grid cells with NO2 levels above 15 µg/m^3. There are exceedances of the WHO guideline for NO_2 of 10 µg/m3 in several cities 2019, especially in the north of Sweden, as well as along major highways. There are still exceedances of the WHO guideline in 2030 in Göteborg, outside Gällivare and at a few receptor points in Stockholm.

Model results of NO_2 in this study show stronger gradients especially close to road emissions due to the higher resolution. Urban background concentration levels of NO_2 exceed 20 µg/m^3 in several cities and close to many major roads in Sweden. Large areas over the three major cities and grid cells in several more cities have modelled concentrations above the WHO guideline of 10 µg/m^3.

For PM10 there are no modelled exceedances of the air quality standard in Alpfjord Wylde et al. (2023) for 2019, however there are modelled exceedances of the air quality objective of 15 µg/m^3 in Göteborg, Malmö and along the major highways, especially along the E6 from Kungälv and southwards and the E4 close to Stockholm. In the scenarios for 2030 there are modelled exceedances of 15 µg/m^3 along major highways, mostly E4 and E6, as well as across a large part of Malmö.

In this more high-resolution study there are some grid cells in Stockholm near the major roads where modelled concentrations exceed the annual air quality standard (40 µg/m^3) in urban background. Exceedances of the air quality objective (15 µg/m^3) have quite similar patterns to the exposure study, with exceedances in Stockholm, Göteborg and Malmö, but also close to major motorways both in the southern and northern parts of Sweden.

For PM2.5 in the exposure study there are no exceedances of the air quality objective nor the air quality standard for PM2.5 in 2019 according to the model calculations. There are exceedances of the WHO guideline of 5 µg/m^3 for the south of Sweden, up to Göteborg, Jönköping, Norrköping and Stockholm in 2019. Several medium sized cities further north, such as Uppsala, Västerås and Sundsvall also exceed the WHO guideline. For PM2.5 for 2030 there is a small reduction in concentrations, resulting in levels below 5 µg/m^3 occurring slightly further south than for 2019. Several medium sized cities in mid Sweden no longer exceed the WHO guideline in 2030 according to the model results.

The air quality objective of PM2.5 (10 µg/m^3) is in this high-resolution study exceeded at several grid cells along the motorway E6/E20 between Malmö and Helsingborg and along major roads within Malmö. This differs compared to the exposure study which did not show any exceedances of the air quality objective. There are also exceedances of the WHO guideline of 5 µg/m^3 in southern Sweden similar to that seen in the exposure study.

4.5 Validation of modelling results

4.5.1 Data quality objectives for air quality modelling

According to Annex 1 in the European Ambient Air Quality Directive (AAQD, 2008/50/EG)[16] the data quality objectives for air quality modelling compared to measurements are defined as ”the maximum deviation of the measured and calculated concentration levels for 90 % of individual monitoring points, over the period considered, by the limit value, without taking into account the timing of the events.” Maximum allowed modelling uncertainties per pollutant and temporal resolution is listed in Table 4.

Table 4. Maximum allowed modelling uncertainty according to the AAQD (2008/50/EG).

Modelling uncertainty	**NO2**	**PM2.5 and PM10**
Hourly	50%	-
Daily	50%	-
Yearly	30%	50%

4.5.1.1 RDE and RPE

Two statistical indicators have been defined to assess the modelling quality as defined in the AAQD; Relative Percentile Error (RPE) and Relative Directive Error (RDE). These are defined as:

$RPE= |O_{perc} - M_{perc}|/M_{perc}$

$RDE= |O_{LV} - M_{LV}|/LV$

where, O is observation, M is modelling result, perc is relevant percentile (or annual mean value when assessing annual mean) and LV is the limit value in the EU Ambient Air Quality Directive. O_{LV} represent the observation closest to the limit value and M_{LV} the corresponding modelling result.

Two indicators are used because they are suitable for different situations, depending on how close the air pollution concentrations are to the limit values.

The benefit of the RDE indicator is that the model is evaluated focused on the limit value. However if the hourly or daily concentration levels are far lower than the limit value, often the case in Sweden, the RPE indicates is a better choice for percentiles. The RDE would in those cases only evaluate the extreme values. For evaluation of the annual mean values however, RDE is recommended for concentrations well below the limit

[16] Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02008L0050-20150918

value, and RPE is preferred for annual mean values that are close to or higher than the limit values[17]. Both RDE and RPE is presented below for all urban measurement stations.

4.5.1.2 Modelling quality objective (MQO)

The indicators RDE and RPE are simple indicators to apply, however many factors are not considered with such unrefined measures, such as timing of events between measurement and model and the fact that the measurement uncertainty differs depending on pollution level. A better way to measure modelling quality has been developed in the framework of FAIRMODE[18]. The software DELTA tool[19], has been developed to support European air quality modellers in the diagnostics and assessment of air quality modelling performances under the AAQD (European Commission, 2022).

DELTA tool compares modelled and measured timeseries of pollutant concentrations in given locations. A minimum data availability (currently 75%) is required for statistics to be produced at a given measurement station. The software calculates a number of statistical indicators and a Model Quality Objective (MQO)[20], defined as the minimum level of quality to be achieved by a model for policy use. The MQO is constructed on the basis of the observation uncertainty.

How well model results compare to measurements at a station, according to the MQO, can be visualized in a Target diagram. If the station is plotted inside the green circle (T<1) the MQO is fulfilled. The Target diagram also provides information about whether the model error is dominated by bias (either negative or positive), by correlation or standard deviation. MQO must be fulfilled for at least 90% of the available stations.

In the proposal for the revised AAQD in 2022[21] the MQO is suggested to substitute the current definition with RPE and RDE indicators.

4.5.2 Summary of the validation

A model validation was carried out where model results were compared to urban background measurements as well as local traffic sites. Urban background model results were validated before an urban bias correction was applied, in order to ensure sufficient model quality also where there are no urban background measurements available.

In summary, the modelling system passes the validations for urban background concentrations of NO_2, PM10 and PM2.5 according to the MQO defined in FAIRMODE. For local traffic sites the modelling system passes the validation for PM2.5. For NO2 the MQO is partly fulfilled as the daily MQO is passed when motorway sites have been

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[17] Swedish Reference laboratory for modelling recommendations (in Swedish): https://www.smhi.se/reflab/kvalitetssakring/kvalitetssakring/kvalitetsmal

[18] FAIRMODE (Forum for Air Quality Modelling in Europe):https://fairmode.jrc.ec.europa.eu/

[19] DELTA tool: https://aqm.jrc.ec.europa.eu/

[20] FAIRMODE guidance document on modelling quality objectives and benchmarking (version 3.3): https://data.europa.eu/doi/10.2760/41988

[21]Proposal for a revision of the Ambient Air Quality Directives:

https://environment.ec.europa.eu/publications/revision-eu-ambient-air-quality-legislation_en excluded from the statistical analysis. For PM10 local traffic sites do not pass the MQO due to some stations with high standard deviation. The spring peaks of PM10 are hard to model both in terms of timing and magnitude.

4.5.3 NO_2

4.5.3.1 Validation at urban background sites

Urban background concentrations of NO_2 without the application of a correction factor are in general underestimated, with the exception of Stockholm sites where levels are overestimated by the model. When applying a correction factor the modelled levels are very similar to measured levels, see Figure .

In Figure 19 the Target diagram from the DELTA tool software shows the comparison of model results to urban background measurements of NO_2. There were 13 stations available with hourly data, of which 12 had a minimum data availability of 75%. The Modelling Quality Objective (MQO) is passed for 12 out of 12 stations. The quality objective is thus met for more than 90% of the stations and the modelling system is of sufficient quality according to the validation method recommended by FAIRMODE.

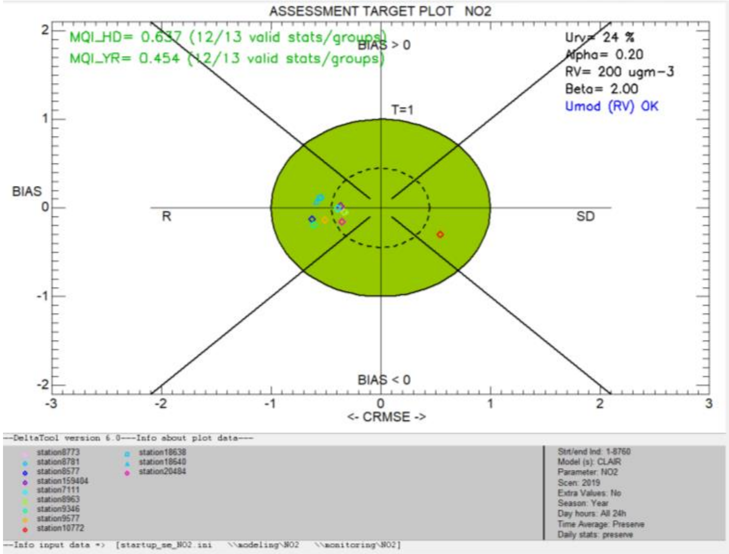

Figure 19. Target plot for NO_2 at urban background sites without urban correction.

The indicators RDE and RPE are calculated for NO_2 annual mean and the hourly and daily 98th percentile, and presented for urban background stations in Table 5. As the concentration levels are low, the RDE for the annual mean is considered the best indicator. Model results pass the annual mean quality objective which is less than 0.3 or 30% for all stations. The quality objective is fulfilled for most percentiles where 90% of the stations are below 0.5 except the daily 98^{th} percentile where two stations exceed the RDE at 0.5.

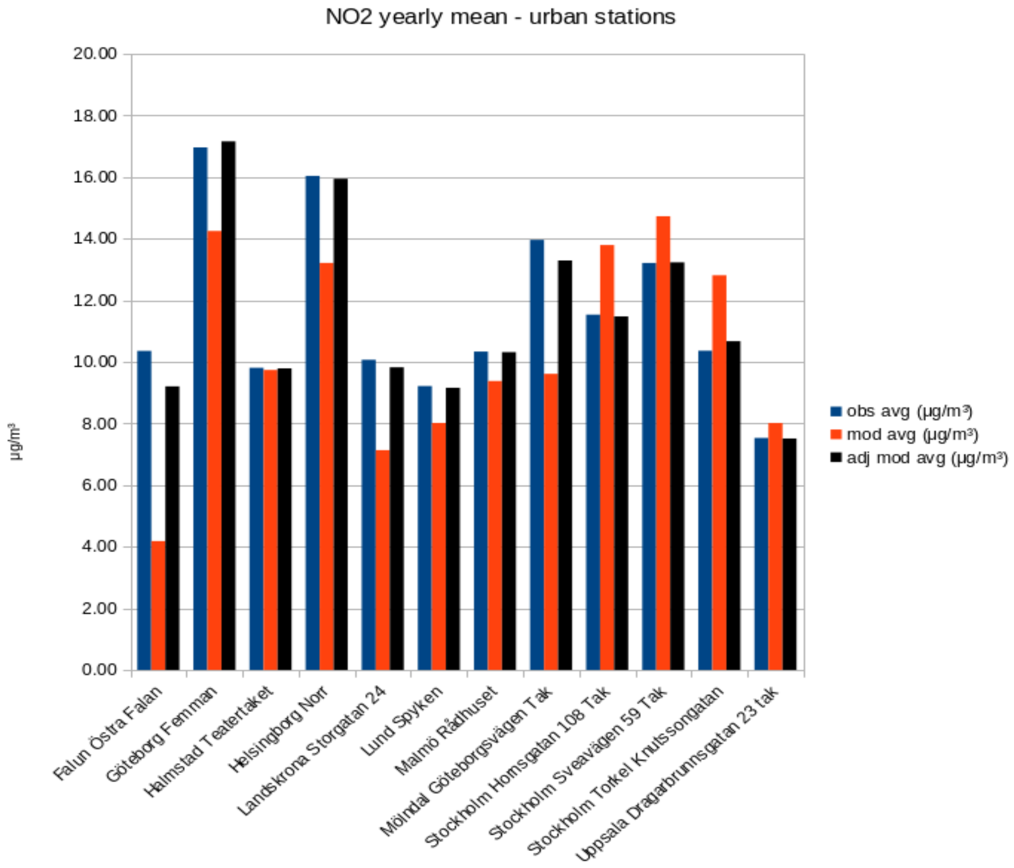

Figure 20. Observed and modelled annual mean of NO_2 at urban background sites. Modelled results include a regional and urban contribution. Measurement stations with lower data coverage than 75% have been excluded.

Table 5. RPE and RDE values for NO_2 at urban background sites.

Urban background sites	RDE Annual mean	RDE Hourly 98 perc.	RPE Hourly 98 perc.	RDE Daily 98 perc.	RPE Daily 98 perc.
Falun Östra Falan	0.15	0.66	0.64	0.61	0.67
Göteborg Femman	0.07	0.17	0.11	0.28	0.3
Halmstad Teatertaket	0	0.22	0.02	0.08	0.12
Helsingborg Norr	0.07	0.34	0.07	0.26	0.25
Landskrona Storgatan 24	0.07	0.3	0.36	0.29	0.29
Lund Spyken	0.02	0.14	0.2	0.22	0.26
Malmö Rådhuset	0.02	0.01	0.03	0.06	0.1
Mölndal Götebrogsvägen	0.11	0.43	0.4	0.53	0.45
Stockholm Hornsgatan 108	0.06	0.39	0.42	0.19	0.4
Stockholm Hornsgatan 59	0.04	0.23	0.44	0.06	0.3
Stockholm Torkel Knutssongatan	0.06	0.23	0.31	0.13	0.44
Uppsala Dragarbrunnsgatan 23	0.01	0.25	0.07	0.22	0.06
Max value	0.15	0.66	0.64	0.61	0.67

4.5.3.2 Validation at local traffic sites

Modelled NO_2 concentrations at local traffic sites are generally somewhat overestimated. With the modelled street canyon contribution concentrations increase and at some sites this results in model overestimations compared to measurements (Figure 19). The street canyon effect is obvious for several sites, in particular for the Stockholm sites. For a number of sites, the model corresponds well with measurements, e.g. in Borås, Karlstad, Lund and Södertälje.

High NO_2 levels are observed at sites near motorways with large traffic load (e.g. Stockholm Lilla Essingen and Göteborg Gårda) and classic street canyon sites (e.g. Stockholm Hornsgatan, Stockholm Sveavägen, Borås Kungsgatan and Skellefteå Viktoriagatan).

At local traffic sites, not including open sites near motorways (Figure 23), the modelling results do not pass the MQO. A few sites (such as Malmö Dalaplan B and Helsingborg M1) show low correlation and high bias. When including motorways in the statistical analysis the MQO is not passed (Figure 22).

Furthermore, when the urban correction factor has been applied modelled concentrations have generally increased, apart from some sites where urban background stations do not exist nearby and thus no correction is applied.

For the local traffic site Göteborg Gårda the urban correction factor has increased the concentration levels and the model consequently overestimates compared to measurements. There are two urban background stations in Göteborg; Göteborg Femman and Mölndal Göteborgsvägen Tak. Both these sites will affect the modelling result at Gårda, and since they are both underestimated, urban levels are adjusted upward. The urban sites may be influenced by a nearby local source which may be affecting the Göteborg Gårda site to a lesser degree (e.g. nearby road and the shipping fairway passing near Femman) and thus does not represent the background levels at the Gårda site to a similar degree. Furthermore, a local source could also potentially either be missing or underestimated in the emission input data for the model, thus leading to underestimated urban concentrations. This shows the difficulty in applying correction factors to a modelling result, as both input data and the representativeness of the measurements have uncertainties. The correction factor thus risks transferring and enhancing any already existing errors to the overall result.

Relatively high modelled concentrations can be observed at Stockholm E4/E20 Lilla Essingen, Göteborg Gårda and Sollentuna E4 Häggvik. The common denominator for these sites is their close proximity to motorways without surrounding buildings thus not defined as street canyons. The Stockholm Lilla Essingen site is also located at several meters height above ground, something that is not accounted for in the model. Wind speeds at this site are probably significantly higher than what the model captures, leading to overestimation of concentrations in the model. Since this type of environment is not described in the model and few people spend time in similar environments, Stockholm Lilla Essingen is not considered a suitable evaluation site for the overall model performance.

Large underestimation can be seen for Sundsvall Köpmansgatan and Malmö Bergsgatan and is explained by lack of input data. These roads are missing in the national road network compiled by the Swedish road administration and thus no input data is generated from these roads to neither the urban model NG2M nor the street canyon model OSPM. These sites have thus been omitted from the evaluation of the modelling result in this study. Input data for these roads need to be improved in a future project.

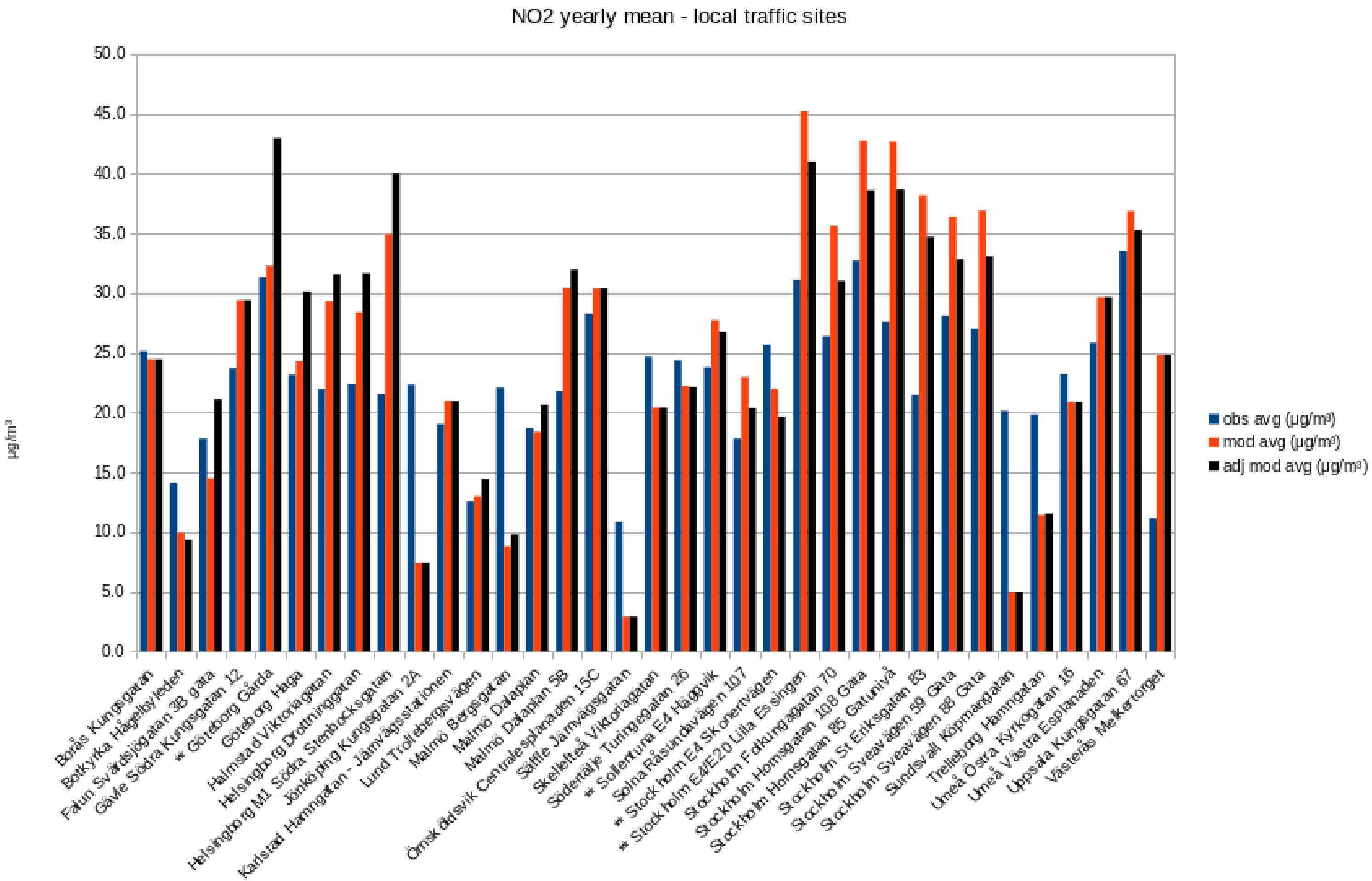

*Figure 21. Observed and modelled annual means of NO_2 at local traffic sites. Red bars signify modelled values without urban correction. Black bars signify modelled values including urban correction. Total model concentrations in street canyons include regional, urban and street canyon contributions. A majority of the stations are traffic stations within street canyons. Stations marked with ** are local traffic stations near motorways. Measurement stations with lower data coverage than 75% have been excluded.*

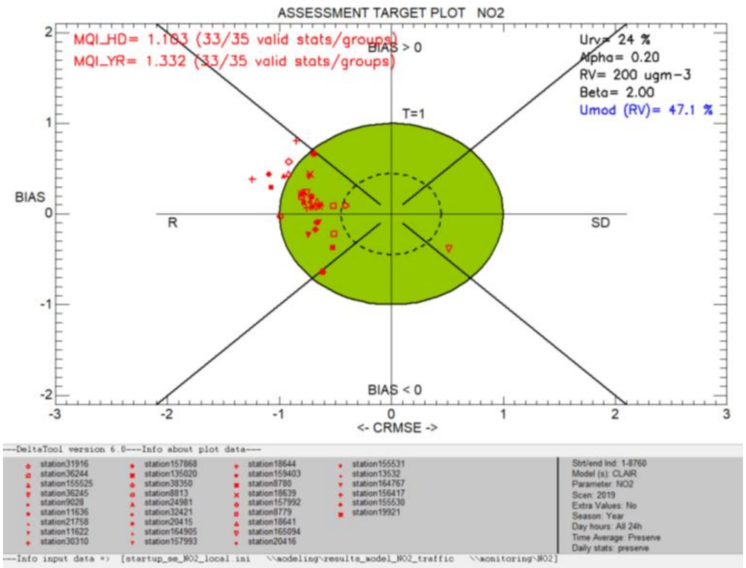

Figure 22. Target plot for NO_2 at local traffic sites, including sites near motorways.

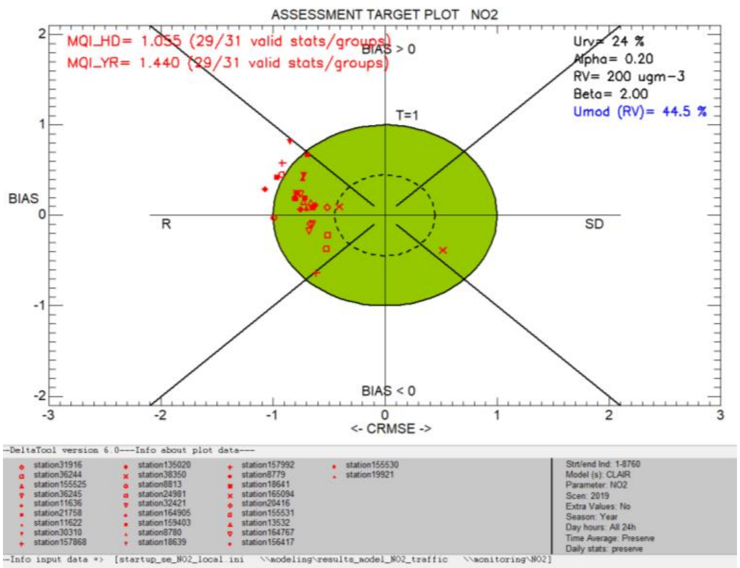

Figure 23. Target plot for NO_2 at local traffic sites, excluding sites near motorways.

The indicators RDE and RPE for the NO_2 annual mean and the hourly and daily 98th percentile at traffic stations, are presented in Table 6. As the concentration levels are low, the RDE for the annual mean is considered the best indicator. Model results do not pass the annual mean quality objective as four stations indicate RDE values above 0.3. This means that 88% of the stations pass the objective. The modelled percentiles do not pass the quality objective either, here 15-35% of the analysed stations show relatively large RPE and RDE values exceeding 0.5.

Table 6. RPE and RDE for NO_2 annual means and percentiles at traffic stations.

Traffic sites	RDE Annual mean	RDE Hourly 98 perc.	RPE Hourly 98 perc.	RDE Daily 98 perc.	RPE Daily 98 perc.
Borås Kungsgatan	0.01	0	0.07	0.18	0.2
Botkyrka Hågelbyleden	0.11	0.4	0.41	0.61	0.46
Falun Svärdsjögatan3B	0.08	0.17	0.17	0.01	0.15
Gävle Södra Kungsgatan 12	0.14	0.12	0.14	0.02	0.07
Göteborg Gårda	0.29	0.69	0.69	0.6	0.53
Göteborg Haga	0.17	0.68	0.59	0.62	0.44
Helsingborg Drottninggatan	0.23	0.75	0.35	0.38	0.25
Helsingborg Södrastenbocksgatan	0.45	1.32	0.78	0.94	0.73
Karlstad Hamngatan	0.05	0.11	0.1	0.08	0.07
Jönköping Kungsgatan 2A	0.37	0.52	0.56	0.63	0.6
Lund Trollebergsvägen	0.05	0.37	0.2	0.01	0.18
Malmö Dalaplan	0.05	0.51	0.37	0.1	0.2
Malmö Dalaplan 5B	0.25	1.38	0.76	0.49	0.65
Skellefteå Viktoriagatan	0.1	0.16	0.17	0.16	0.17
Sollentuna E4 Häggvik	0.07	0.12	0.12	0.03	0.04
Solna Råsundavägen	0.06	0.43	0.29	0.62	0.21
Stockholm E4/E20 Lilla Essingen	0.25	0.93	0.74	0.48	0.47
Stockholm E4skonertvägen	0.15	0.08	0.07	0.2	0.23
Stockholm Folkungagatan70	0.12	0.42	0.31	0.46	0.15
Stockholm Hornsgatan108	0.15	0.3	0.3	0.31	0.34
Stockholm Hornsgatan85	0.28	0.41	0.35	0.54	0.3
Stockholm St. Eriksgatan8	0.33	0.98	0.65	0.66	0.49
Stockholm Sveavägen59	0.11	0.33	0.2	0.07	0.13
Stockholm Sveavägen88	0.15	0.43	0.35	0.12	0.19
Säffle Järnvägsgatan	0.19	0.8	0.78	0.62	0.78
Södertälje Turingegatan	0.06	0.06	0.05	0.06	0.11
Trelleborg Hamngatan	0.2	0.36	0.44	0.32	0.42
Umeå Västraesplanaden	0.09	0.05	0.05	0.12	0.19
Umeå Östra kyrkogatan	0.06	0.16	0.16	0.27	0.3
Uppsala Kungsgatan	0.04	0.19	0.21	0.01	0.12
Västerås Melkertorget	0.33	0.65	0.97	0.35	0.84
Örnsköldsvik Centralesplanaden	0.05	0.05	0.07	0.04	0.08
Max value	0.45	1.38	0.97	0.94	0.84

4.5.3.3 Percentiles

There are several limit values for percentiles for NO_2 concentrations. Apart from the current air quality standards there are new limit values suggested in the revised air quality directive and guidelines from WHO, see Table 7.

Table 7. The concentration levels corresponding to the current air quality standards, proposed new standards, air quality objectives and WHO guidelines for percentiles of NO_2 (unit µg/m^3).

NO2	Time resolution	Percentile	Maximum allowed
Air quality standard[22]	Hour	98	90
Air quality objective[23]	Hour	98	60
Air quality standard	Hour	99.8	200
Proposal in directive[24]	Hour	99.99	200
Air quality standard	Day	98	60
Proposal in directive	Day	95.1	50
WHO Guideline[25]	Day	99	25

At urban background stations no percentile limit values are exceeded, indicated by both observed and modelled levels (Appendix 1a). The model generally underestimates the percentiles (apart from three Stockholm sites) and the urban correction brings levels very close to that of the measurements (Appendix 1b). For local traffic sites, the newly suggested daily 95.1 percentile limit value was exceeded at 9 sites (Appendix 1b). The model also indicated exceedances for these sites apart from Umeå Östra Kyrkogatan, where the 95.1 percentile was underestimated. Furthermore, the model showed exceedances for an additional 10 sites while observations showed no exceedance. This mismatch between model and observation can be seen for several of the percentiles (Appendix 1b) and is partly due to the general overestimation of NO_2 percentile levels by the model at traffic sites. Differences between model and observations become more noticeable for extreme values and modelling these is known to be difficult since these usually occur at specific conditions which themselves are difficult to reproduce (such as stable weather conditions).

Further work is needed for the modelling system to correctly assess percentiles, especially for traffic stations. The higher the percentile the harder it is for the model to reproduce measurements since the number of data points being compared are very few and this increases the possibility for error due to random or very rare effects.

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[22] The Swedish air quality standards: https://www.naturvardsverket.se/globalassets/vagledning/luft-och-klimat/mkn-utomhusluft/sammanstallning-miljokvalitetsnormer.pdf

[23] The Swedish environmental quality objectives for clean air: https://www.naturvardsverket.se/en/environmental-work/environmental-objectives/clean-air/

[24] Proposal for a revision of the Ambient Air Quality Directives:

https://environment.ec.europa.eu/publications/revision-eu-ambient-air-quality-legislation_en

[25] WHO global air quality guidelines: https://apps.who.int/iris/bitstream/handle/10665/345329/9789240034228-eng.pdf?sequence=1&isAllowed=y

4.5.4 PM10

4.5.4.1 Validation at urban background sites

At urban background sites the model produces good results, with small differences in PM10 levels between measurements and model (Figure 23). At Göteborg Femman the model overestimates the yearly mean by 1 µg/m3 and in Malmö underestimates by 1.3 µg/m^3.

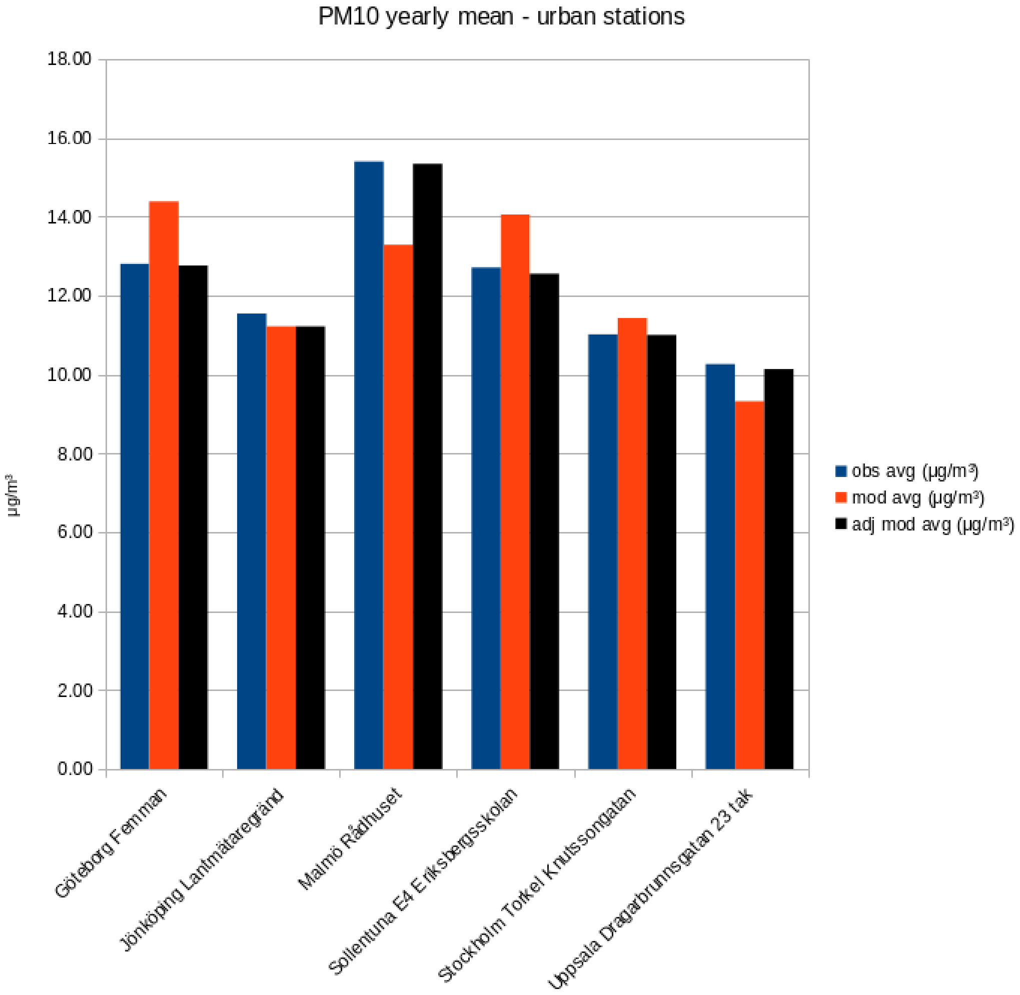

Figure 24. Observed and modelled yearly means of PM10 at urban background sites. Model values contain regional and urban contribution. Measurement stations with lower data coverage than 75% has been excluded.

In Figure 25 all urban background PM10 stations in the Target plot pass the MQO. There are notably only 5 stations available on an hourly resolution in urban background. The diagram shows that the model errors are dominated by low correlation, a common problem when modelling PM10.

The indicators RDE and RPE are calculated for the PM10 annual mean and shown in Table 8. As the concentration levels are low, the RDE for the annual mean is considered the best indicator. Model results pass the annual mean quality objective as all stations show RDE values below 0.5. For the daily 90th percentile no thresholds exist but has relatively low RPE and RDE values with a maximum RDE at 0.26 (26%).

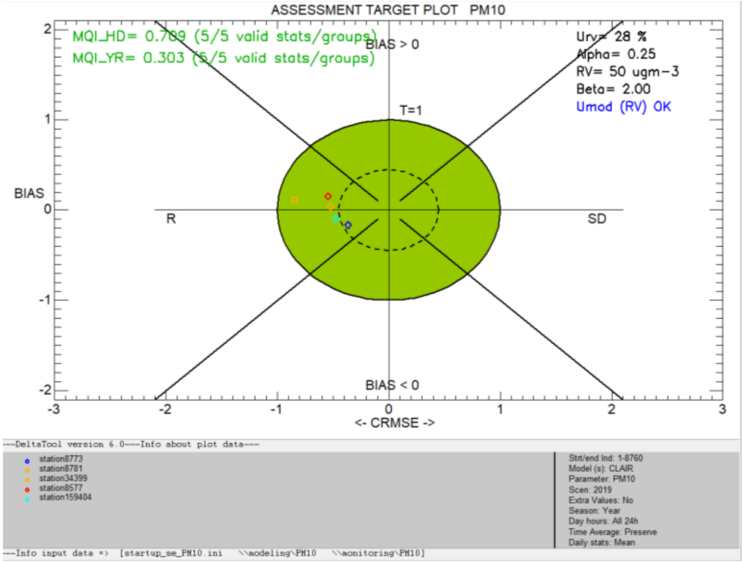

Figure 25. Target plot for PM10 at urban background sites without urban correction.

Table 8. RDE and RPE for PM10 at urban background sites.

Urban Background sites	RDE Annual mean	RDE Daily 90 perc.	RPE Daily 90 perc.
Göteborg Femman	0.03	0.09	0.1
Malmö Rådhuset	0.05	0.15	0.17
Sollentuna E4 Eriksbergsskolan	0.03	0.15	0.05
Stockholm Torkel Knutssongatan	0.01	0.14	0.07
Uppsala Dragarbrunnsgatan 24	0.02	0.26	0.25
Max value	0.05	0.26	0.25

4.5.4.2 Validation at local traffic sites

The general pattern observed for PM10 at local traffic sites is that the model underestimates concentrations compared to measurements (Figure *25*). At some sites the model produces good results where model and measurements correspond well (Borås, Göteborg Gårda, Halmstad, Malmö Dalaplan, Örebro, Västerås, Växjö). At other sites (e.g. Piteå, Sundsvall, Skellefteå, Säffle, Visby) considerable underestimations can be seen and may partly be explained by inadequate description and information of anti-slip methods e.g. the amount of sand being applied to roads in winter time. In the case of Sundsvall Köpmansgatan input data for traffic is missing since the road itself is missing in the national road database. Therefore no traffic emissions are calculated in the NG2M and OSPM models at this site and concentrations are thus underestimated.

The urban correction factor mostly improves the overall result, however there are still some sites where differences are considerable between observed and modelled levels. Overestimated PM10 levels at motorways (Sollentuna E4 Häggvik, Sollentuna Ekmans väg 11, Stockholm E4/E20 Lilla Essingen) can potentially be explained by insufficient description of the relationship between vehicle speed and roadwear in the current model implementation, resulting in an excessive emission generation in the NORTRIP model.

Furthermore, Sollentuna Ekmans väg 11 (E4), is a major road descended between two walls on each side creating a natural canyon, however the placement of the measurement station is behind the wall (eastward of the road) and a few meters above ground, thus the inlet of the station does not capture the direct emission plume from the road. The urban NG2M model does not include support for this type of topography and this would also partly explain the overestimation at this site. Thus the measurement station is not representative of the model results and is omitted from the evaluation of the model performance, but still shown in the bar plot figure for illustrative reasons.

The MQO is just about fulfilled for the annual values when stations at motorways are excluded, but not fulfilled with stations at motorways included (Figure 27 and 28) due to some stations that show a large standard deviation and bias.

The indicators RDE and RPE are calculated for the PM10 annual mean at traffic stations and shown in Table 9. As the concentration levels are low, the RDE for the annual mean is considered the best indicator. Model results pass the quality objective for the annual mean where all stations show RDE below 0.5. For the daily percentile no model quality objective exists, however 85-89% of the stations show RPE and RDE below 0.5.

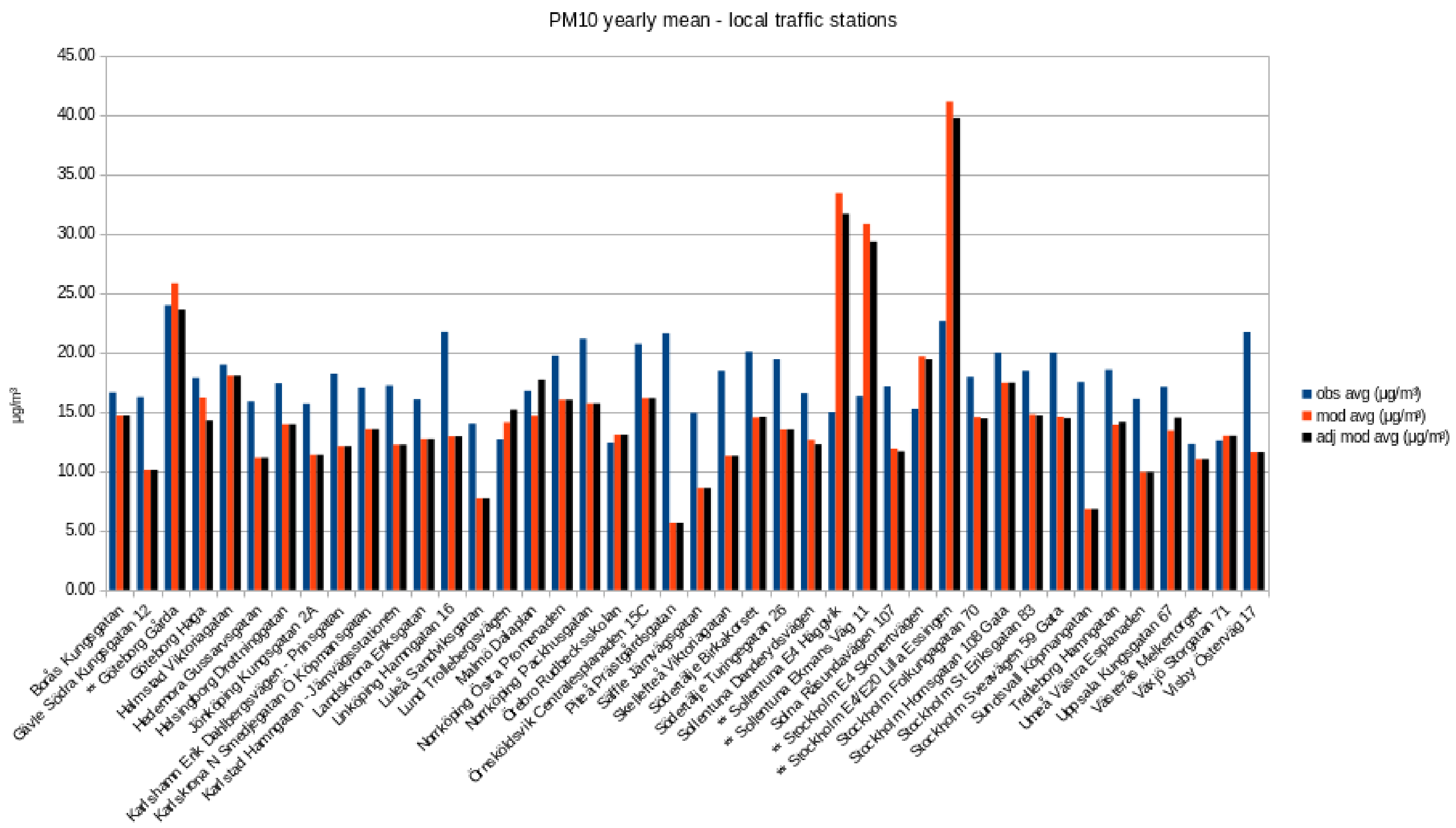

*Figure 26. Observed and modelled annual means of PM10 at local traffic sites. Red bars signify modelled values without urban correction. Black bars signify modelled values including urban correction. The total model concentrations at street level include regional, urban and street canyon contributions. Stations marked with ** are local traffic stations near motorways. Measurement stations with lower data coverage than 75% has been excluded.*

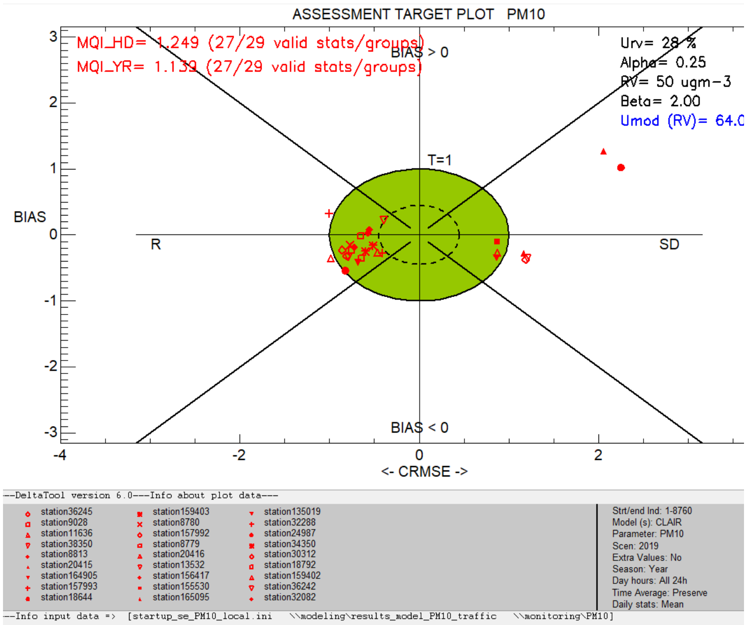

Figure 27. Target plot for PM10 at local traffic sites.

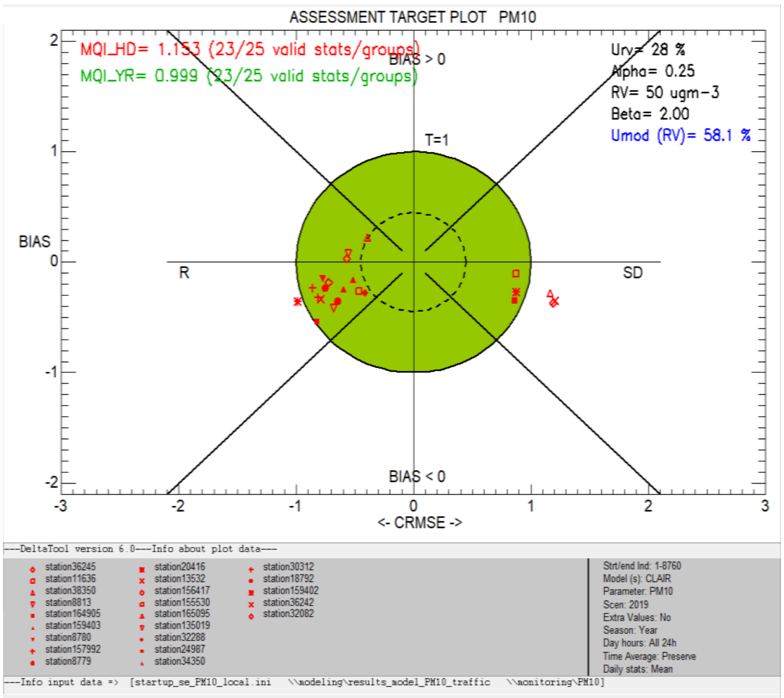

Figure 28. Target plot for PM10 at local traffic sites that have a street canyon contribution (sites near motorways are excluded).

Table 9. RPE and RDE for PM10 annual mean and percentile at traffic stations.

Traffic Sites	RDE Annual mean	RDE Daily 90 perc	RPE Daily 90 perc
Gävle Södra Kungsgatan12	0.15	0.58	0.44
Göteborg Gårda	0	0.16	0.18
Göteborg Haga	0.08	0.23	0.29
Hedemora Gussarvsgatan	0.12	0.5	0.42
Karlshamn Erik Dahlbergsvägen	0.14	0.33	0.39
Karlskrona Norra Smedjegatan	0.09	0.08	0.13
Linköping Hamngatan16	0.22	0.46	0.46
Lund Trollebergsvägen	0.06	0.03	0.05
Malmö Dalaplan	0.02	0.05	0
Norrköping Packhusgatan	0.13	0.33	0.33
Norrköping Östra promenaden	0.09	0.27	0.28
Sollentuna E4 Häggvik	0.42	1.36	0.69
Sollentuna Danderydsvägen	0.11	0.43	0.25
Sollentuna Ekmans väg11	0.32	0.64	0.66
Solna Råsundavägen107	0.14	0.47	0.4
Stockholm E4E20 Lilla Essingen	0.42	0.94	0.91
Stockholm E4 Skonertvägen	0.1	0.5	0.27
Stockholm Folkungagatan 70	0.09	0.21	0.17
Stockholm Hornsgatan 108	0.06	0.12	0.11
Stockholm St. Eriksgatan 83	0.09	0.32	0.31
Stockholm Sveavägen 59	0.13	0.29	0.33
Södertälje Birkakorset	0.14	0.35	0.39
Södertälje Turingegatan 26	0.15	0.45	0.36
Umeå Västra esplanaden	0.15	0.41	0.41
Uppsala Kungsgatan 67	0.06	0.28	0.28
Västerås melkertorget	0.03	0.44	0.23
Växjö Storgatan 71	0.01	0.1	0.1
Max value	0.42	1.36	0.91

4.5.4.3 Percentiles

There are several daily percentiles defined for PM10 concentrations. Apart from the current air quality standard there is a new limit value suggested in the revised air quality directive and a guideline from WHO, see Table 10.

Table 10. The concentration levels corresponding to the current air quality standards, proposed new standards, air quality objectives and WHO guidelines for percentiles of PM10 (unit µg/m³).

PM10	Time resolution	Percentile	Limit value
Air quality standard[26]	Day	90	50
Air quality objective[27]	Day	90	30
Proposal in directive[28]	Day	95.1	45
WHO Guideline[29]	Day	99	45

For urban background stations there are no modelled nor measured exceedances of PM10 percentile limit values, neither for current nor proposed standards nor the Swedish environmental objective. For the WHO Guideline, the 99th percentile is exceeding 45 µg/m³ at Malmö Rådhuset and Sollentuna Eriksbergsskolan (Appendix 2a).

The model generally underestimates PM10 levels, as has been seen for annual averages with the exception of the Göteborg Femman site. Looking at the percentiles for local traffic stations (Appendix 2b) no sites show exceedances for the current daily air quality standard of 50 µg/m³ apart from three sites in Stockholm where the model result exceeds the limit value. For the 95.1 percentile several measurement sites show exceedances, however the model does not match this and rather underestimates the percentile at several sites. Regarding the WHO guideline all local traffic measurement sites exceed the limit value of 45 µg/m³, while the model shows fewer sites with exceedances.

4.5.5 PM2.5

4.5.5.1 Validation at urban background sites

In urban background the model produces good results compared to most measurement sites with small differences in PM2.5 levels (Figure 29. At Stockholm Torkel Knutssonsgatan the model overestimates the annual mean by 1.2 µg/m3 and in Malmö the model underestimates by ca. 1 µg/m3. The urban correction of modelled concentrations works relatively well for most sites and adjusts the model levels to measurements. Sometimes however, two background stations (Burlöv and Malmö Rådhuset) are located in close proximity. The correction at the Burlöv site is thus also influenced by the Malmö Rådhuset site and modelled levels increase here instead of decreasing as would be the expectation.

Figure 30 shows the Target plot for all PM2.5 urban background stations. There are only five stations on an hourly resolution of which four have data availability over 75%. These four stations pass the MQO with a large margin. For PM2.5 the model error is dominated by correlation issues.

[26] The Swedish air quality standards: https://www.naturvardsverket.se/globalassets/vagledning/luft-och-klimat/mkn-utomhusluft/sammanstallning-miljokvalitetsnormer.pdf

[27] The Swedish environmental quality objectives for clean air: https://www.naturvardsverket.se/en/environmental-work/environmental-objectives/clean-air/

[28] Proposal for a revision of the Ambient Air Quality Directives:

https://environment.ec.europa.eu/publications/revision-eu-ambient-air-quality-legislation_en

[29] WHO global air quality guidelines: https://apps.who.int/iris/bitstream/handle/10665/345329/9789240034228-eng.pdf?sequence=1&isAllowed=y

The indicators RDE and RPE are calculated for the PM2.5 annual mean and are shown in Table 11. As the concentration levels are low, the RDE for the annual mean is considered the best indicator. All urban background stations show RDE below 0.5 and the model quality objective is thus passed.

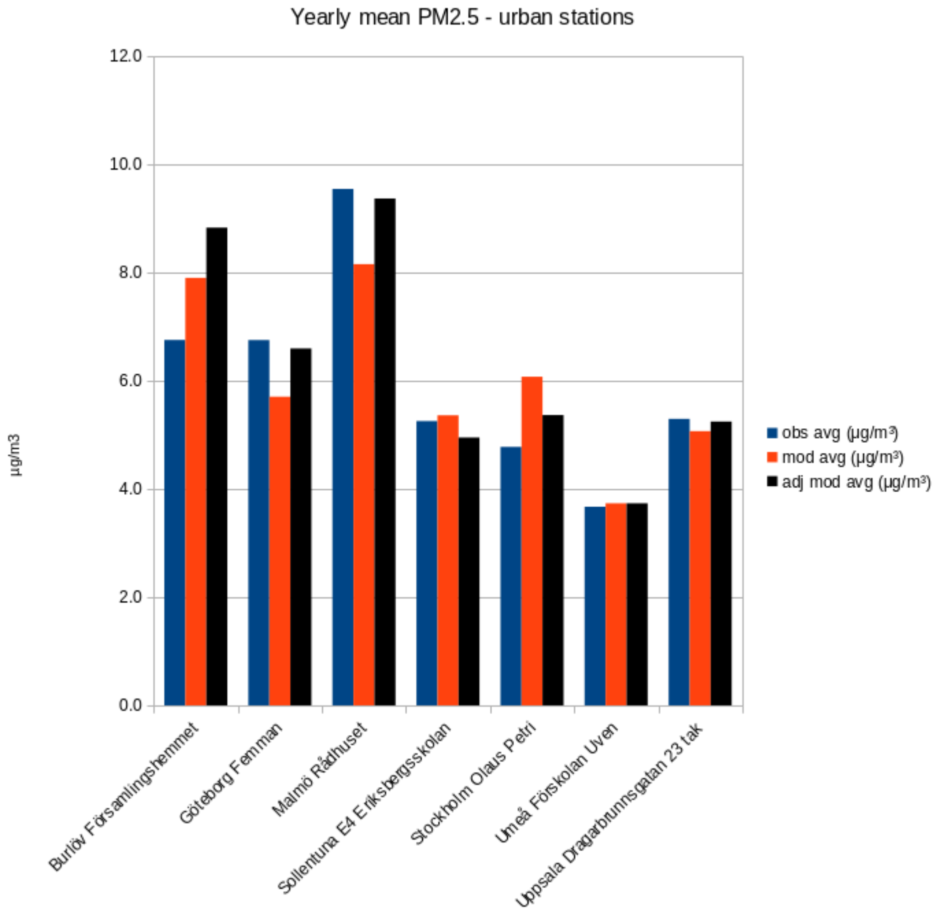

Figure 29. Observed and modelled annual means of PM2.5 at urban background sites. Model results include a regional and an urban contribution. Measurement stations with lower data coverage than 75% have been excluded.

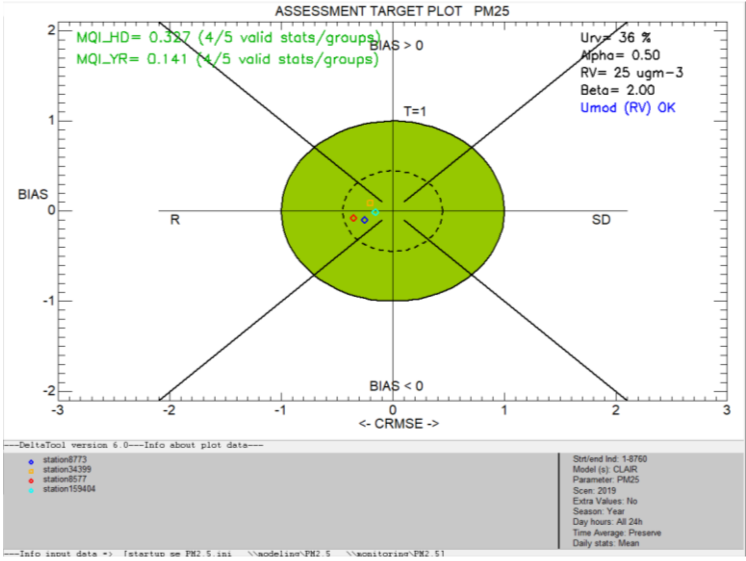

Figure 30. Target plot for PM2.5 at urban background sites without urban correction.

Table 11. RDE and RPE for the annual mean of PM2.5 at urban background stations.

Urban background site	RDE Annual mean
Göteborg Femman	0.04
Malmö Rådhuset	0.04
Sollentuna E4 Eriksbergsskolan	0.03
Stockholm Torkel Knutssongatan	0.05
Uppsala Dragarbrunnsgatan 23	0
Max value	0.05

4.5.5.2 Validation at local traffic sites

The model produces good results for PM2.5 at a majority of the local traffic sites (Figure 31). This is also reflected in the Target plot where MQO is fulfilled and all sites are within the inner circle (Figure 32). The correlation with measurements is relatively high and the bias is low. The good result is also further confirmed with RDE values well below 0.5 for traffic stations (Table 13). PM2.5 is dominated to a large degree by the regional background and concentrations are generally low across Sweden. Southern sites (e.g. Malmö) commonly receive a significant regional contribution due to its vicinity to Copenhagen and continental Europe.

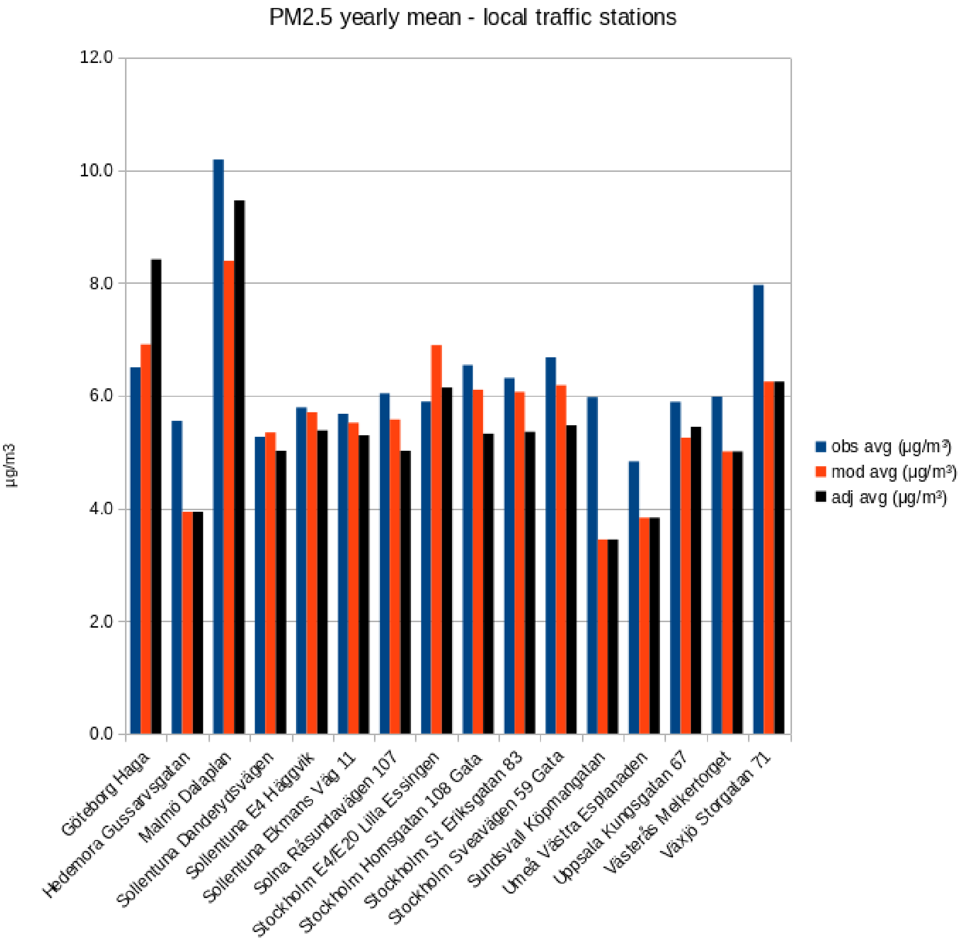

Figure 31. Observed and modelled annual means of PM2.5 at local traffic sites. Red bars signify modelled values without urban correction. Black bars signify modelled values including urban correction. The total model concentrations at street level include regional, urban and street canyon contributions. Measurement stations with lower data coverage than 75% have been excluded.

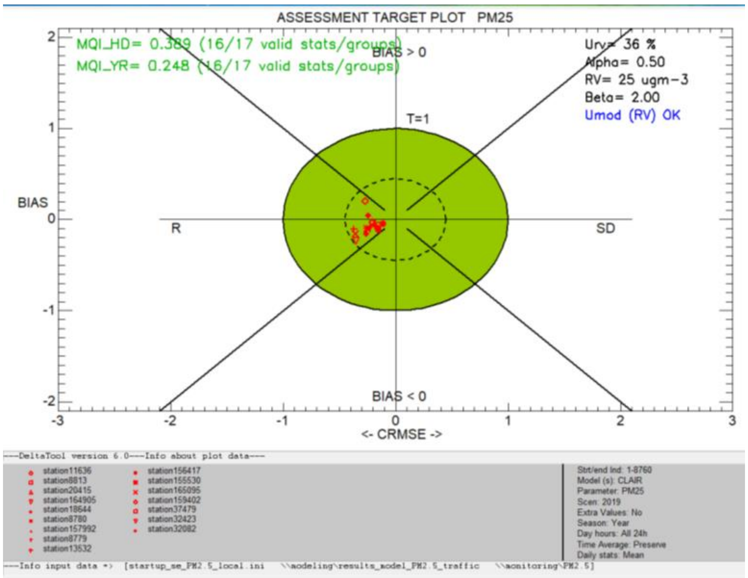

Figure 32. Target plot for PM2.5 at local traffic sites, including sites at motorways.

Table 12. RDE for PM2.5 annual mean at traffic stations.

Traffic sites	RDE Annual mean
Göteborg Haga	0.04
Hedemora Gussarvsgatan	0.04
Malmö Dalaplan	0.02
Sollentuna E4 Häggvik	0.01
Sollentuna Danderydsvägen	0.01
Sollentuna Ekmansväg 11	0.01
Solna Råsundavägen	0.03
Stockholm E4/E20 Lilla Essingen	0.01
Stockholm Hornsgatan108	0.03
Stockholm ST. Eriksgatan 83	0.02
Stockholm Sveavägen 59	0.03
Sundsvall Bergsgatan	0.06
Umeå Västra esplanaden	0.03
Uppsala Kungsgatan 67	0.01
Västerås Merkeltorget	0.02
Växjö Storgatan 71	0.04
Max value	0.06

4.5.5.3 Percentiles

In the current directive there is no standard for percentiles for PM2.5, only for the annual mean. However, there are daily percentiles defined in the revised directive proposal, as well as a Swedish air quality objective and a WHO guideline, see Table 13.

Table 13. The concentration levels corresponding to the proposed new air quality standard, the air quality objective and WHO guideline for percentiles of PM2.5 (unit µg/m³).

PM2.5	Time resolution	Percentile	Maximum allowed
Proposal in directive[30]	Day	95.1	25
Air quality objective[31]	Day	99	25
WHO Guideline[32]	Day	99	15

When looking at percentile values for PM2.5 there are relatively small differences between observations and model (Appendix 3a and 3b), with the exception of sites Sundsvall Bergsgatan and Sundsvall Köpmansgatan. For the daily 95.1 percentile with limit value 25 only Malmö Dalaplan shows an exceedance, indicated by both model and measurement. All other sites are below this limit value. For the more stringent limit value (99th percentile with limit value 15) it becomes obvious that for a few sites the model does not perform as well in capturing the more extreme values, however for the majority of the sites the differences are low even for this more extreme percentile. The modelling performance is overall quite good for PM2.5.

4.6 Challenges

Previously in air quality modelling, dispersion modelling projects could either be screening projects covering large areas, or more detailed studies for a limited area. In this project a large effort has been made to optimize the whole modelling chain, in order to enable performing modelling over large areas with very high resolution and also including street canyon contributions. To the best of our knowledge, no such high-resolution modelling over such large areas has been done before.

Once a 10x10 km tile has been calculated and postprocessed, the gridded timeseries results for that tile is deleted by the CLAIR system. The reason for this is storage. Each single 10x10 km tile requires about 7 GB storage for gridded timeseries, which leads to more than 25 TB of data for the whole modelling domain. The cost associated with such storage capacities is currently too large, therefore only yearly averages and percentiles are stored in the final results. Being able to store also timeseries of grid cells would allow the results to be re-used further than what only storing statistical fields allows for.

4.7 Future work and improvements

The developed methodology includes a number of different models, and a large amount of input data. All models and input datasets have uncertainties. In addition, the monitoring data used for evaluation and correction also have uncertainties.

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[30] Proposal for a revision of the Ambient Air Quality Directives:

https://environment.ec.europa.eu/publications/revision-eu-ambient-air-quality-legislation_en

[31] The Swedish environmental quality objectives for clean air: https://www.naturvardsverket.se/en/environmental-work/environmental-objectives/clean-air/

[32] WHO global air quality guidelines: https://apps.who.int/iris/bitstream/handle/10665/345329/9789240034228-eng.pdf?sequence=1&isAllowed=y

The presented evaluation can be used to identify which pollutants and under which conditions the modelling chain as a whole can be improved. However, in order to improve the different models or input information, further systematic analysis of deviations between measured and modelled concentrations is often needed. Some potential improvements have already been identified, but remain to be implemented or require additional evaluation, while others require deeper evaluation.

4.7.1 Improvements of emissions

Emissions are considered one of the most important sources of uncertainties. The most important sources in Sweden are road traffic (exhaust and non-exhaust) as well as residential wood combustion. In some specific areas individual point-sources and shipping may also have significant impact on the concentrations.

Exhaust emissions from road traffic are fairly well described, but may be improved by more complete traffic information or improved traffic modelling, especially for roads maintained by municipalities. Further improvements are also possible when it comes to describing congestion (level-of-service).

Non-exhaust emissions are more uncertain. To improve the description of particulate matter at traffic sites (inside street canyons or near major roads), correct parameterisations and input information for the NORTRIP model is essential. The evaluation has shown that PM10 is systematically underestimated in northern Sweden. An attempt has been made to improve the modelled process of sanding in this region, which is common in the northern part of Sweden, but has not solved the problem sufficiently. There is no city in northern Sweden with measurements of PM10 both at street level and roof level (urban background), allowing detailed analysis of the contribution from a single street. Also, having NOx measurements at the same sites would allow evaluation of non-exhaust emissions specifically, without confusion by other uncertainties related to background concentrations, traffic, emission factors or dispersion modelling. A so-called super-site in northern Sweden would greatly improve the possibility to evaluate and improve the NORTRIP application for this region. Systematic overestimation of PM10 near motorways can also be seen. After verifying input information and ensuring that NOx concentrations can be accurately described (implying correct description of dispersion), adjusting for this would be possible by tuning e.g. pavement hardness in the NORTRIP model, effectively reducing wear on motorways. However, any such tuning should be considered a short-term solution. A more sustainable solution would be to support further development of the NORTRIP model.

In general, a critical factor to improve correlation between modelled and measured PM10 at road sites is availability of measured road surface wetness. If road surface wetness can be better estimated using e.g. available measurements together with more common meteorological parameters, this would greatly improve the accuracy of NORTRIP results. Further evaluation of this possibility is recommended.

Detailed data for shipping emissions already exists, but has only been partly included in the current methodology. A possible improvement would be to include hourly shipping emissions with high spatial resolution, based on the Shipair modelling system.

A future national register of residential heating appliances is currently being assessed by the Swedish EPA. Such a register has potential to greatly improve the description of emissions from residential wood combustion.

4.7.2 General improvements of dispersion

The urban scale dispersion model NG2M is based on well evaluated gaussian plume formulations. However, the model is today used at higher spatial resolution and applied also to describe concentrations near major roads. Detailed evaluations of similar models have been carried out in other countries (e.g. Norway and Denmark). It would be very valuable to fine-tune parameterisations and evaluate and document model performance using internationally available datasets.

Examples of specific parameterisations would benefit from improvements are:

- Wind and plume parameterisations during stable atmospheric conditions encountered during winter time.
- Near-road dispersion, including the effect of traffic produced turbulence.
- Initial mixing and near-source dispersion from residential wood combustion.

4.7.3 Future improvements for NO_2

Systematic disagreement of NO_2, not explained by corresponding disagreement in NOx, may be minimized by adjusting the parameterisation of the NOx-chemistry scheme. An average distance of 500m between source and receptor is currently assumed representative for urban areas and used to estimate a time scale for turbulent mixing. This distance has for now been set solely based on expert judgement and may be adjusted to better reflect real conditions. This is a relatively simple improvement.

Background concentrations of NOx, NO_2 and O3 at a street-canyon are approximated by the upstream roof-level concentration at each hour. The distance upstream has been noted to be insufficient under some circumstances, and the local street may then influence the background concentrations. This leads to overestimation of NO_2 at some street canyons. This can be likely be solved by increasing the distance upstream where the background concentrations are extracted.

5 Conclusions

This nation-wide mapping of air pollution levels at high resolution has provided an important and useful national base dataset for evaluating air quality in Sweden. It can be used to detect hot spot areas in cities where air quality standards risks being exceeded and it provides valuable information that can be further applied in the development of action plans for air quality mitigation. The dataset can also be further applied in source apportionment of air pollution and assessments of exposure and health effects.

The street canyon contribution was most apparent for NO_2 where canyons were surrounded by buildings on both sides i.e. classic street canyons. In open urban street environments (often near major roads and motorways) there were generally lower or sometimes insignificant street canyon contributions to NO_2 levels. Here the regional and urban contributions produced concentrations well in line with measurements.

For PM10, the urban and regional contributions dominate the total concentrations overall and the street canyon contribution was most apparent at a few sites in cites, most often located near major roads with large traffic load. PM10 has shown to be underestimated at a majority of sites, and for a few sites overestimated, thus the relative significance of the different contributions is somewhat uncertain.

For PM2.5, the regional contribution dominates levels and matched well with observations. Some street canyon contributions were apparent for a few streets in Malmö.

Input data for estimating traffic emissions needs to be updated and missing roads included in the road database network. Where roads are missing interpolation methods could be applied from nearby roads, but is outside the scope of this project. It is recommended that further work be prioritised to improve traffic data (such as time-variations, vehicle fleet, etc.) in order to increase the quality of input data to models.

Modelling extreme values (percentiles) are difficult and in this study, for some sites, relatively large deviations between model and observation has been detected for NO_2 and PM10. Further work is needed to investigate these differences in greater detail.

In the evaluation of the model performance some measurement sites have been omitted due to not being a representative site. Some measurement sites have also been omitted due the lack of input data resulting in an incomplete model result.

In order to further explain the exact causes of the discrepancies between model and observations further studies with more detailed analysis at specific sites are needed to investigate the potential influence from uncertainties originating from input data, meteorology and model descriptions. Especially with focus on NO_2 and PM10. Identifying this is essential in order to further plan and implement improvements of the modelling result.

6 References

Andersson, C., Langner, J., Bergström, R., 2007. Interannual variation and trends in air pollution over Europe due to climate variability during 1958–2001 simulated with a regional CTM coupled to the ERA40 reanalysis. Tellus B Chem. Phys. Meteorol. 59, 77–98. https://doi.org/10.1111/j.1600-0889.2006.00231.x

Andersson, C., Bergström, R., Bennet, C., Robertson, L., Thomas, M., Korhonen, H., Lehtinen, K.E.J., Kokkola, H., 2014. MATCH–SALSA – Multi-scale Atmospheric Transport and CHemistry model coupled to the SALSA aerosol microphysics model – Part 1: Model description and evaluation (preprint). Atmospheric Sciences. https://doi.org/10.5194/gmdd-7-3265-2014

Berkowicz, R., Hertel, O., Larsen, S. E., Sørensen, N. N., & Nielsen, M. (1997). Modelling traffic pollution in streets. National Environmental Research Institute.

Berkowicz et al., 2011: NO2 chemistry scheme in OSPM and other Danish models, Technical note, NERI, Aarhus university. http://www2.dmu.dk/AtmosphericEnvironment/Docs/NO2scheme.pdf

EEA (2022). Air quality in Europe 2022. Report no. 05/2022.

European Commission, Joint Research Centre, Janssen, S., Thunis, P., FAIRMODE guidance document on modelling quality objectives and benchmarking: version 3.3, Publications Office of the European Union, 2022. https://data.europa.eu/doi/10.2760/41988

ExternE (2005). Externalties of Energy – Methodology 2005 Update. Edited by Peter Bickel and Rainer Friedrich, European Commission EUR 21951.

Hult C, Merelli L, Mawdsley I, 2022. Styrmedel för minskade NOX-utsläpp från vägtrafik i scenarier med skärpta EU-krav för fordons CO2-utsläpp. IVL Report nr C 668.

Nilsson Sommar J, Andersson EM, Andersson N, Sallsten G, Stockfelt L, Ljungman PL, Segersson D, Eneroth K, Gidhagen L, Molnar P, Wennberg P, Rosengren A, Rizzuto D, Leander K, Lager A, Magnusson PK, Johansson C, Barregard L, Bellander T, Pershagen G, Forsberg B, 2021. Long-term exposure to particulate air pollution and black carbon in relation to natural and cause-specific mortality: a multicohort study in Sweden. BMJ Open 11(9):e046040.

Omstedt, G., 2007: VEDAIR – ett internetverktyg för bedömning av luftkvalitet vid småskalig biobränsleeldning, SMHI Rapport nr. 123. http://urn.kb.se/resolve?urn=urn:nbn:se:smhi:diva-2215

Robertson, L., Langner, J., Engardt, M., 1999. An Eulerian Limited-Area Atmospheric Transport Model. J. Appl. Meteorol. 38, 190–210. https://journals.ametsoc.org/view/journals/apme/38/2/1520-0450_1999_038_0190_aelaat_2.0.co_2.xml

Segersson D, Eneroth K, Gidhagen L, Johansson C, Omstedt G, Nylén AE, Forsberg B, 2017. Health Impact of PM10, PM2.5 and Black Carbon Exposure Due to Different Source Sectors in Stockholm, Gothenburg and Umea, Sweden. Int J Environ Res Public Health 14(7):742.

Segersson D, Johansson C, Forsberg B, 2021. Near-Source Risk Functions for Particulate Matter Are Critical When Assessing the Health Benefits of Local Abatement Strategies. Int J Environ Res Public Health 18(13):6847.

Segersson, D., 2021. Quantification of population exposure and health impacts associated with air pollution (PhD dissertation, Department of Environmental Science, Stockholm University). Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:su:diva-199214

Segersson, D., Asker, C., Bennet, C., Andersson, C., 2021. Concentrations of NOx in Sweden over three decades using dispersion modelling at local and regional scale. Paper IV as part of dissertation. Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:su:diva-199214

Söderqvist T, Kriit H K, Tidblad J, Andersson J, Jansson S-A, Svensson M, Wallström J, Andersson C, Orru H, Sommar N J, Forsberg B, 2019. Underlag för reviderade ASEK-värden för luftföroreningar: Slutrapport från projektet REVSEK (in Swedish). Trafikverket.

WHO (2021). WHO global air quality guidelines. Particulate matter (PM 2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. World Health Organization.

7 Appendices

Appendix 1a – NO_2 percentiles at urban stations

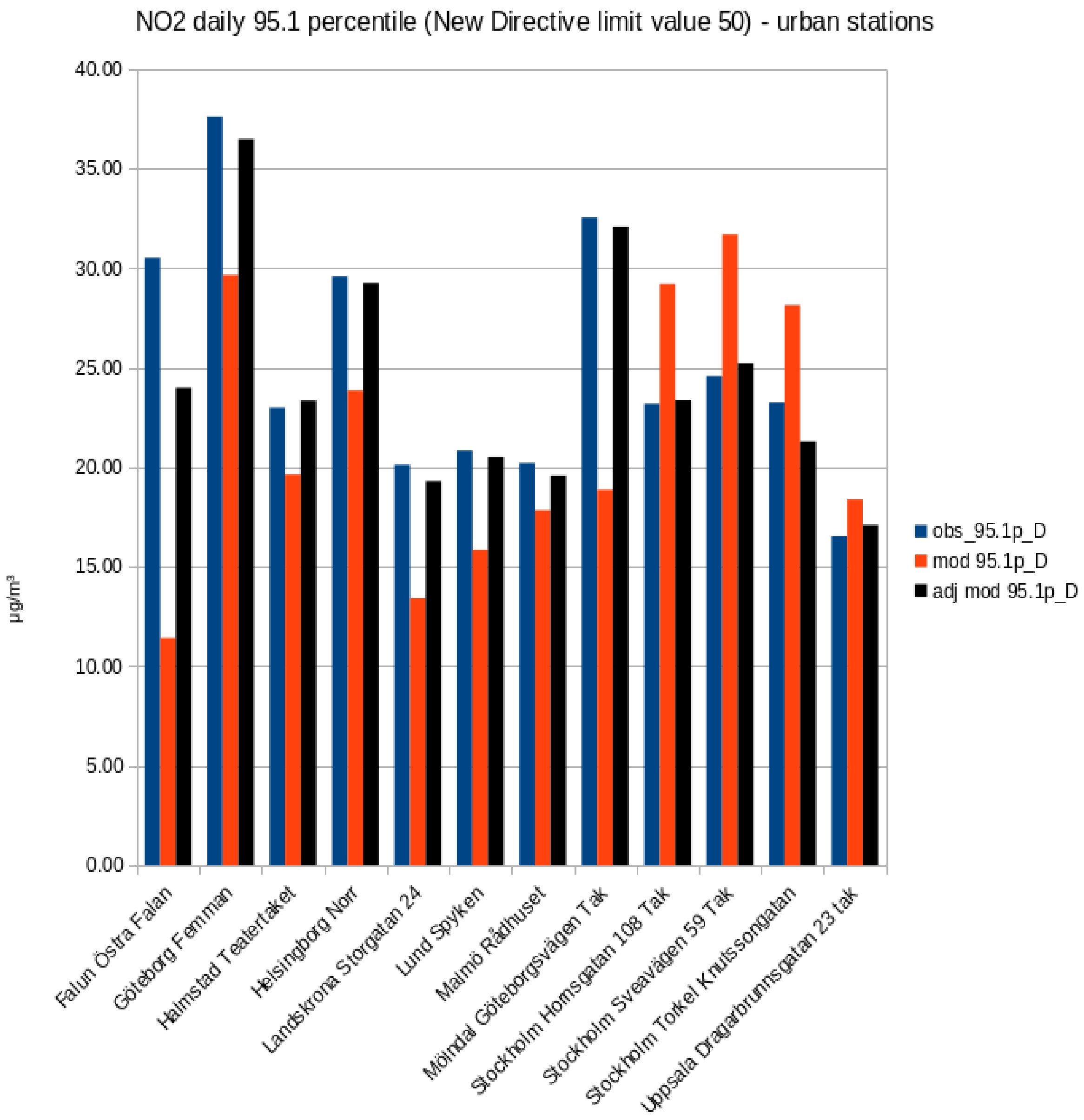

Figure 33. Modelled and observed NO_2 95.1 percentile at urban background sites. This is the new daily limit value at 50 µg/m^3 proposed in the revised EU Ambient Air Quality Directive. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

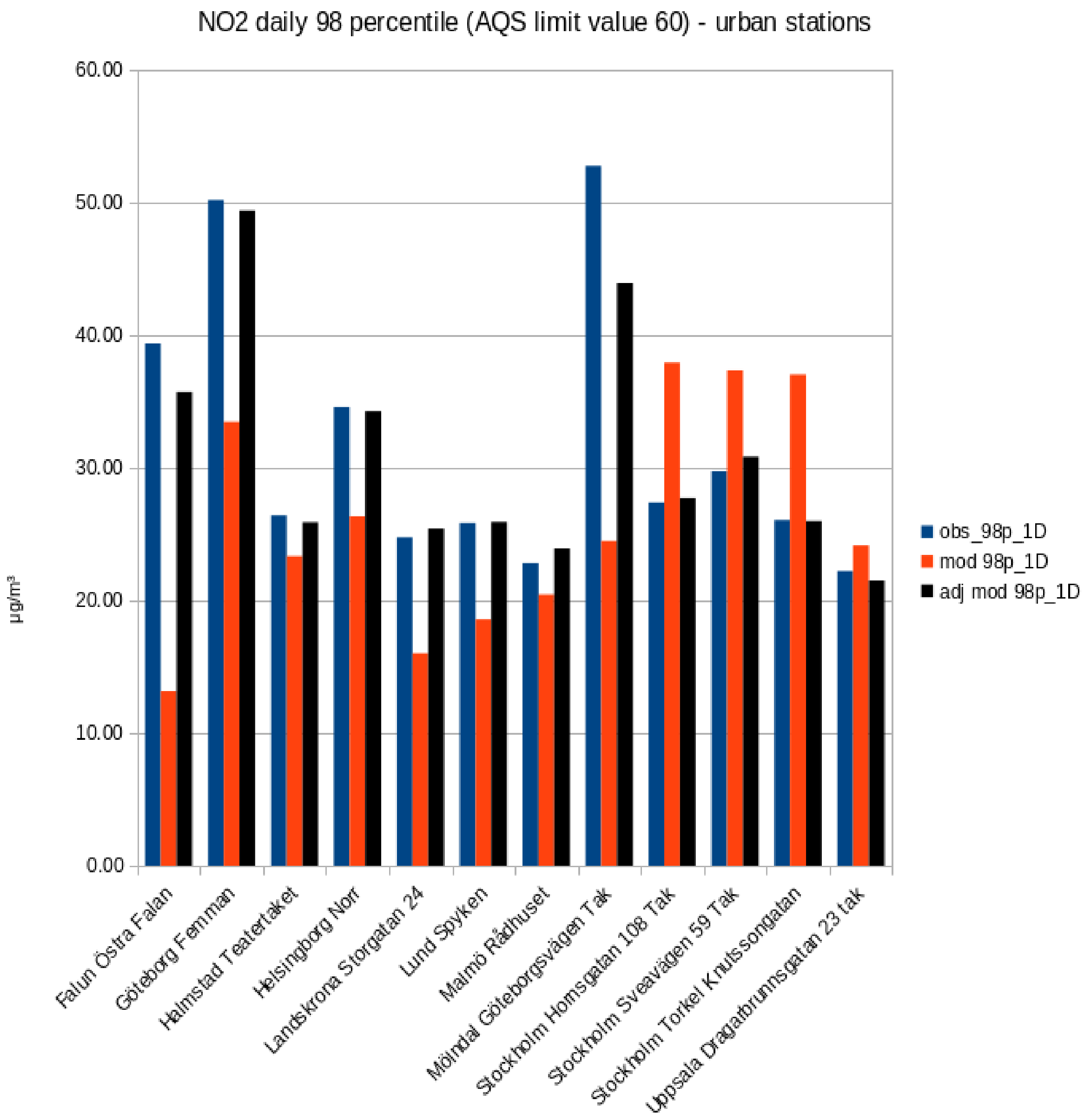

Figure 34. Modelled and observed NO_2 98th percentile at urban background sites. This is the current daily limit value at 60 µg/m^3. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

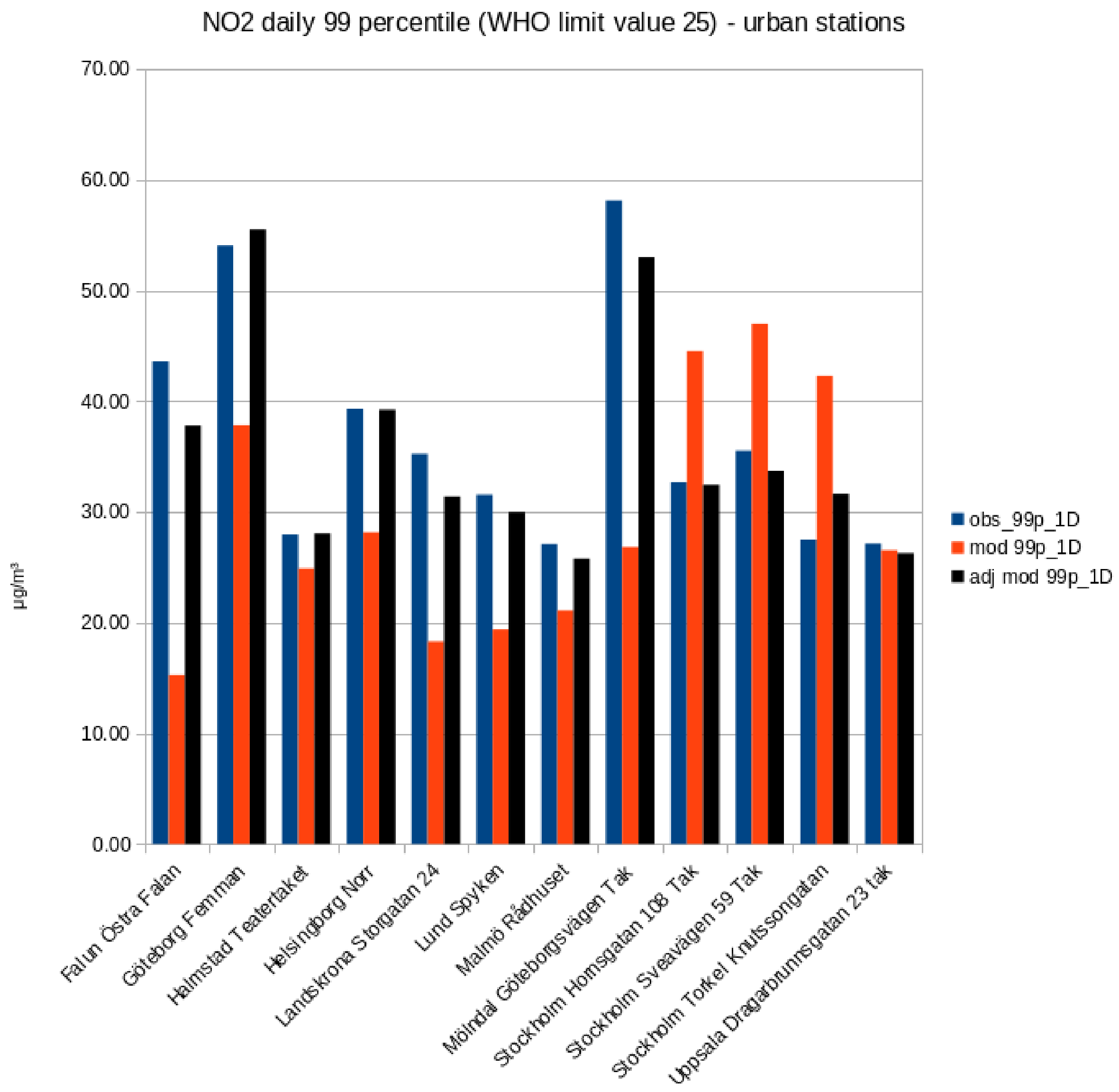

Figure 35. Modelled and observed NO_2 99th percentile at urban background sites. This is the daily limit value at 25 µg/m^3 from the World Health Organisation. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

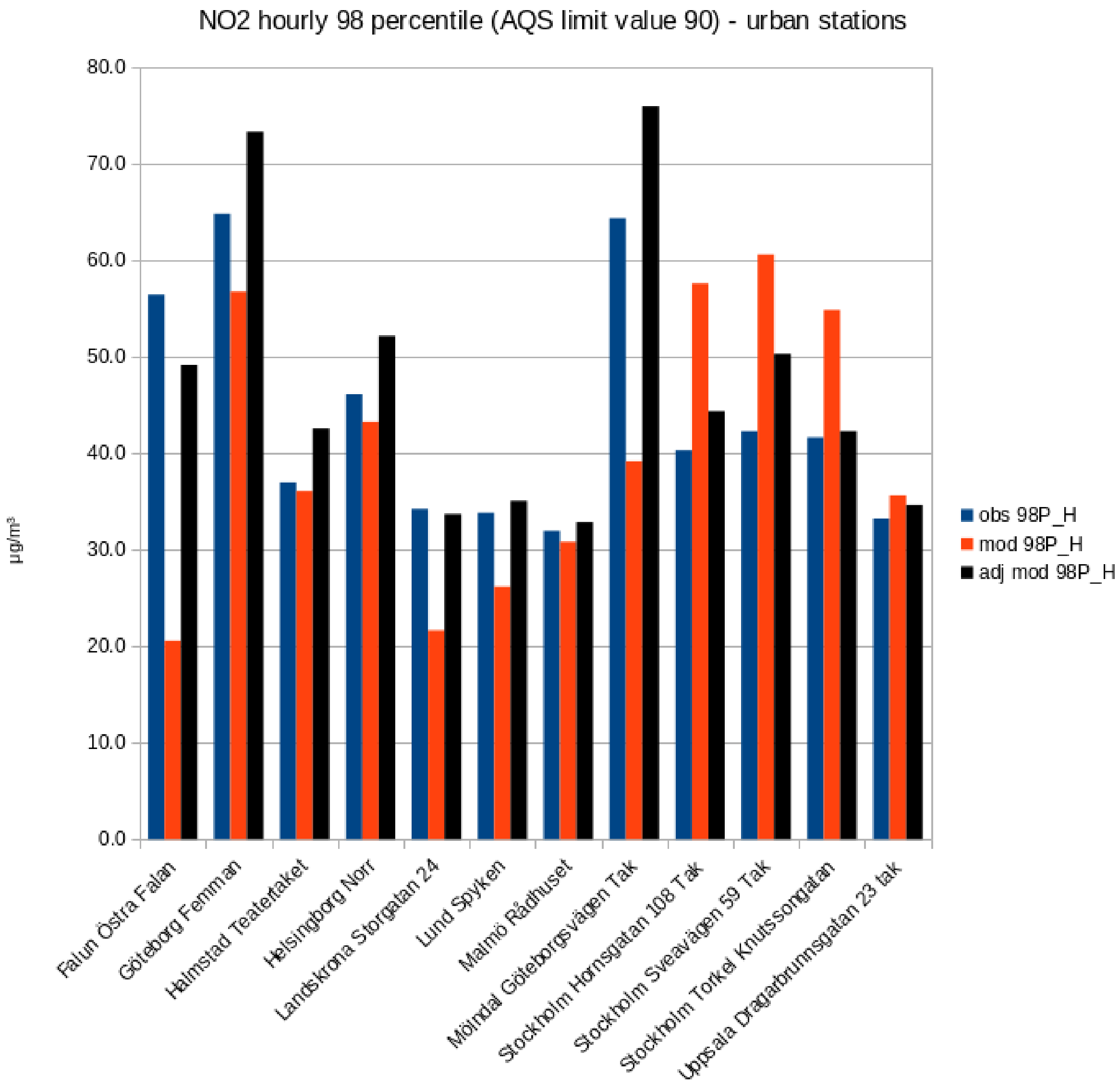

Figure 36. Modelled and observed NO_2 98th percentile at urban background sites. This is the current hourly air quality standard with limit value at 90 µg/m^3 in Sweden. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

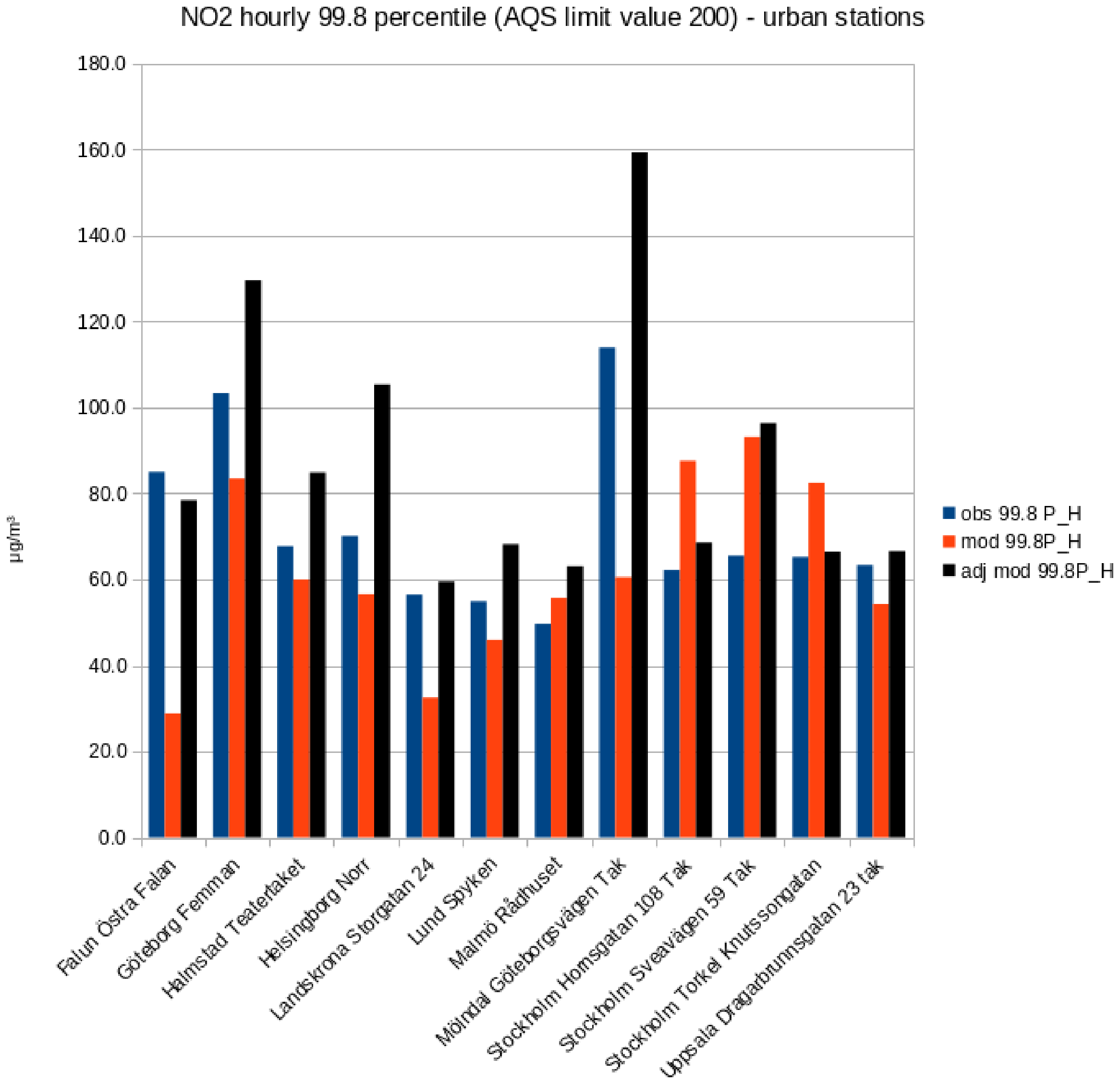

Figure 37. Modelled and observed NO_2 99.8th percentile at urban background sites. This is the current hourly limit value at 200 µg/m^3. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

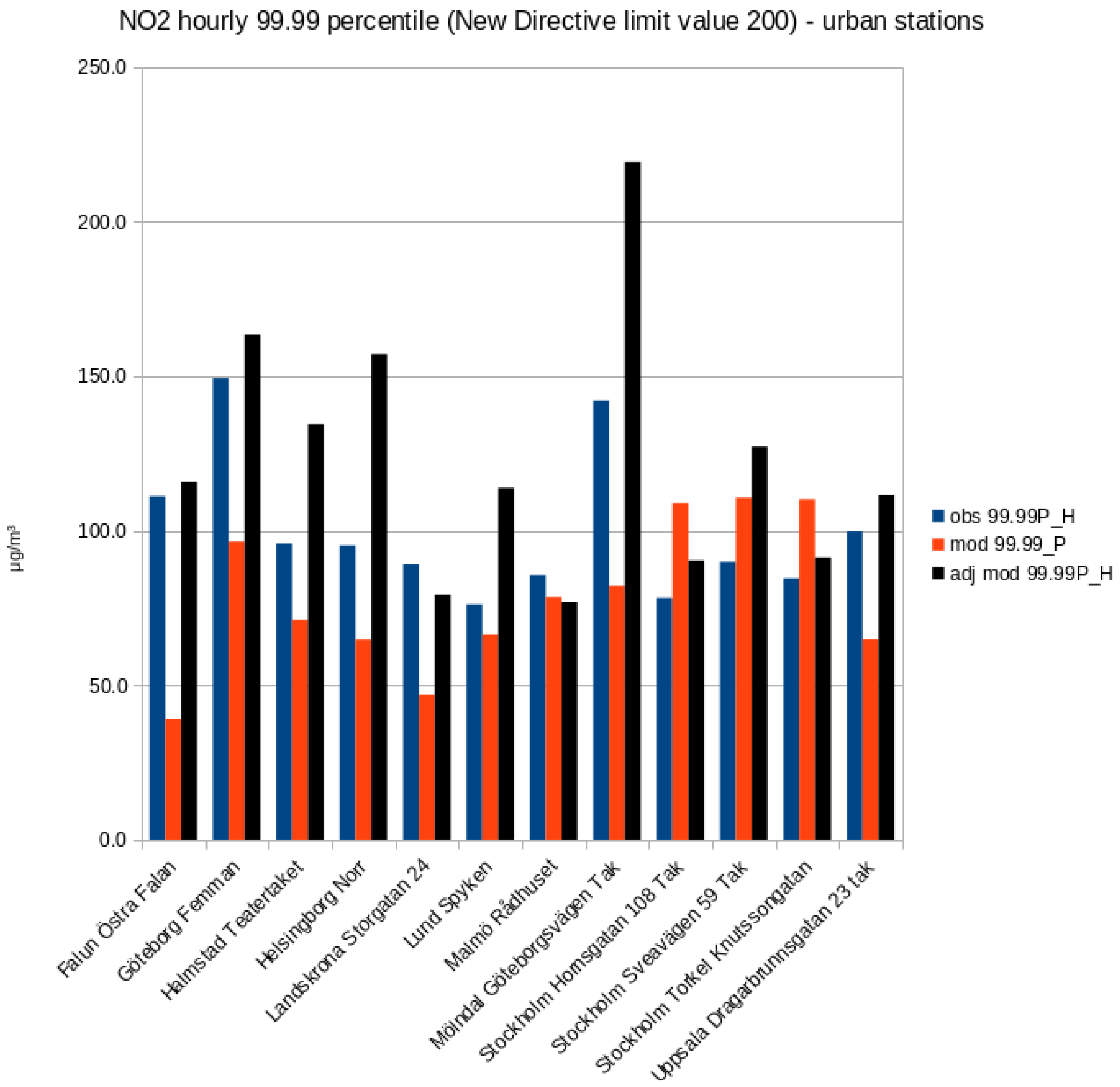

Figure 38. Modelled and observed NO_2 99.99th percentile at urban background sites. This is the new daily limit value at 200 µg/m^3 proposed in the revised EU Ambient Air Quality Directive. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

Appendix 1b – NO_2 percentiles at local traffic stations

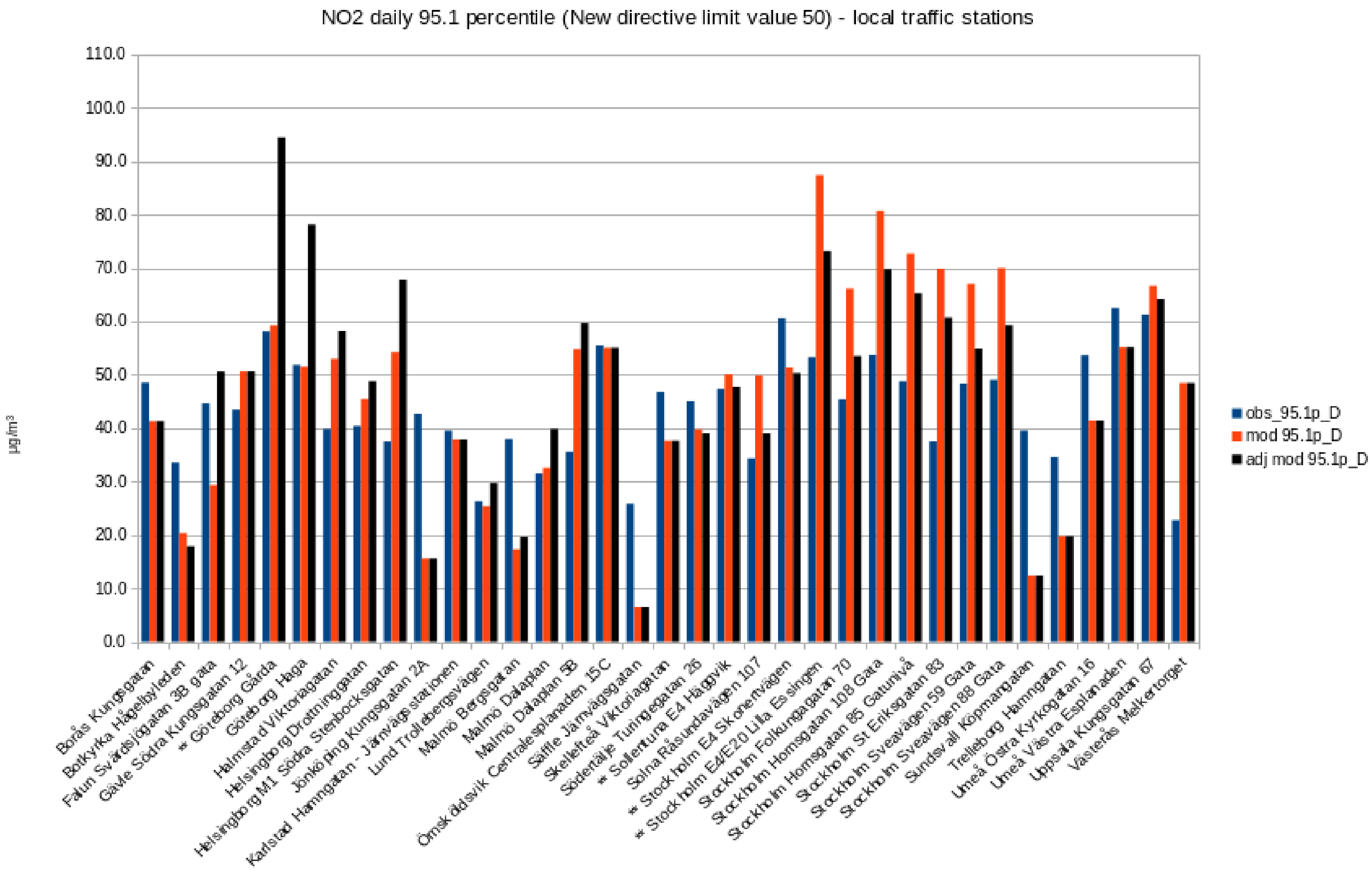

Figure 39. Modelled and observed NO_2 95.1th percentile at local traffic sites. This is the new daily limit value at 50 µg/m^3 proposed in the revised EU Ambient Air Quality Directive. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

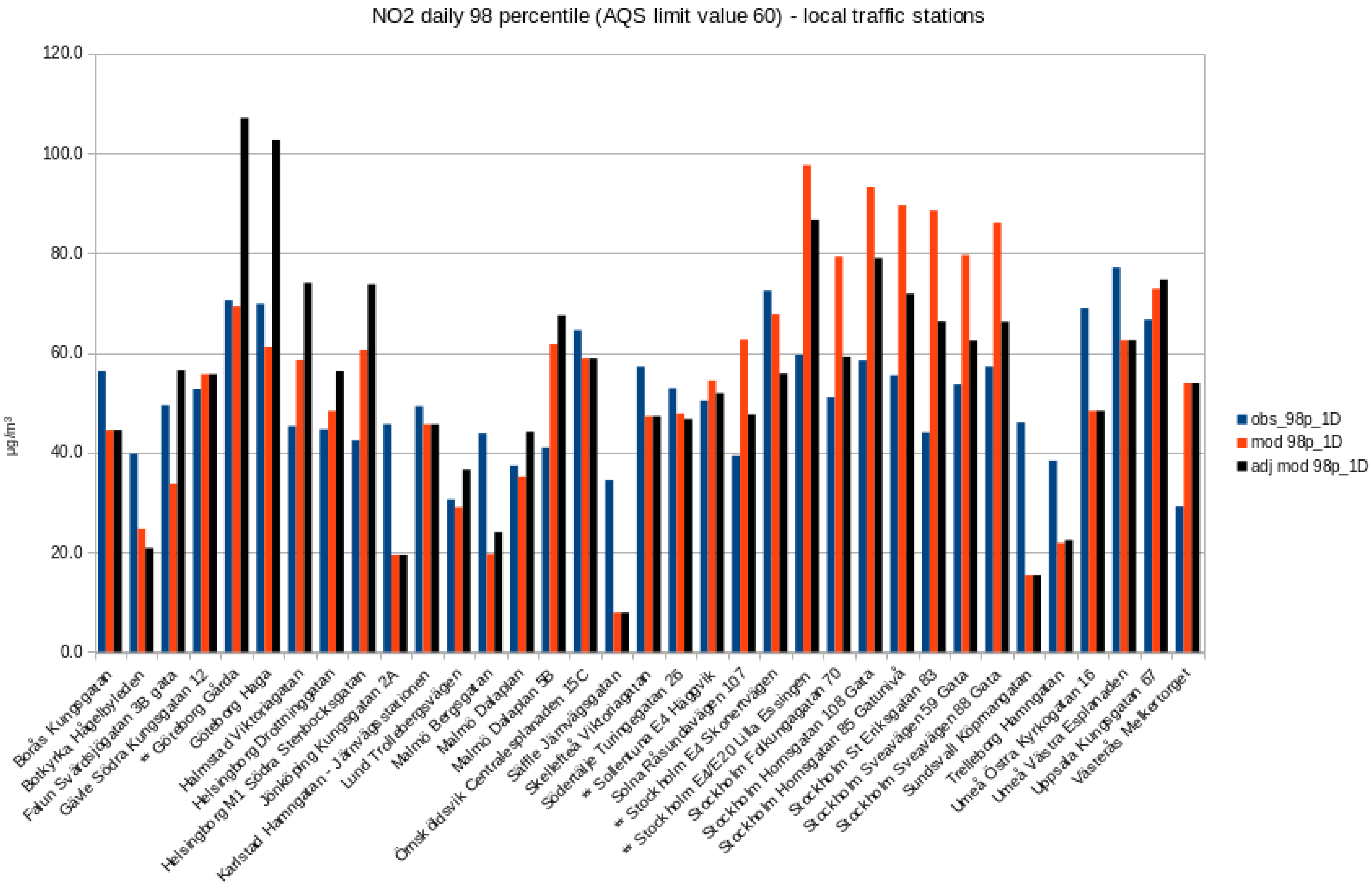

Figure 40. Modelled and observed NO_2 98th percentile at local traffic sites. This is the current daily limit value at 60 µg/m3 in Sweden. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

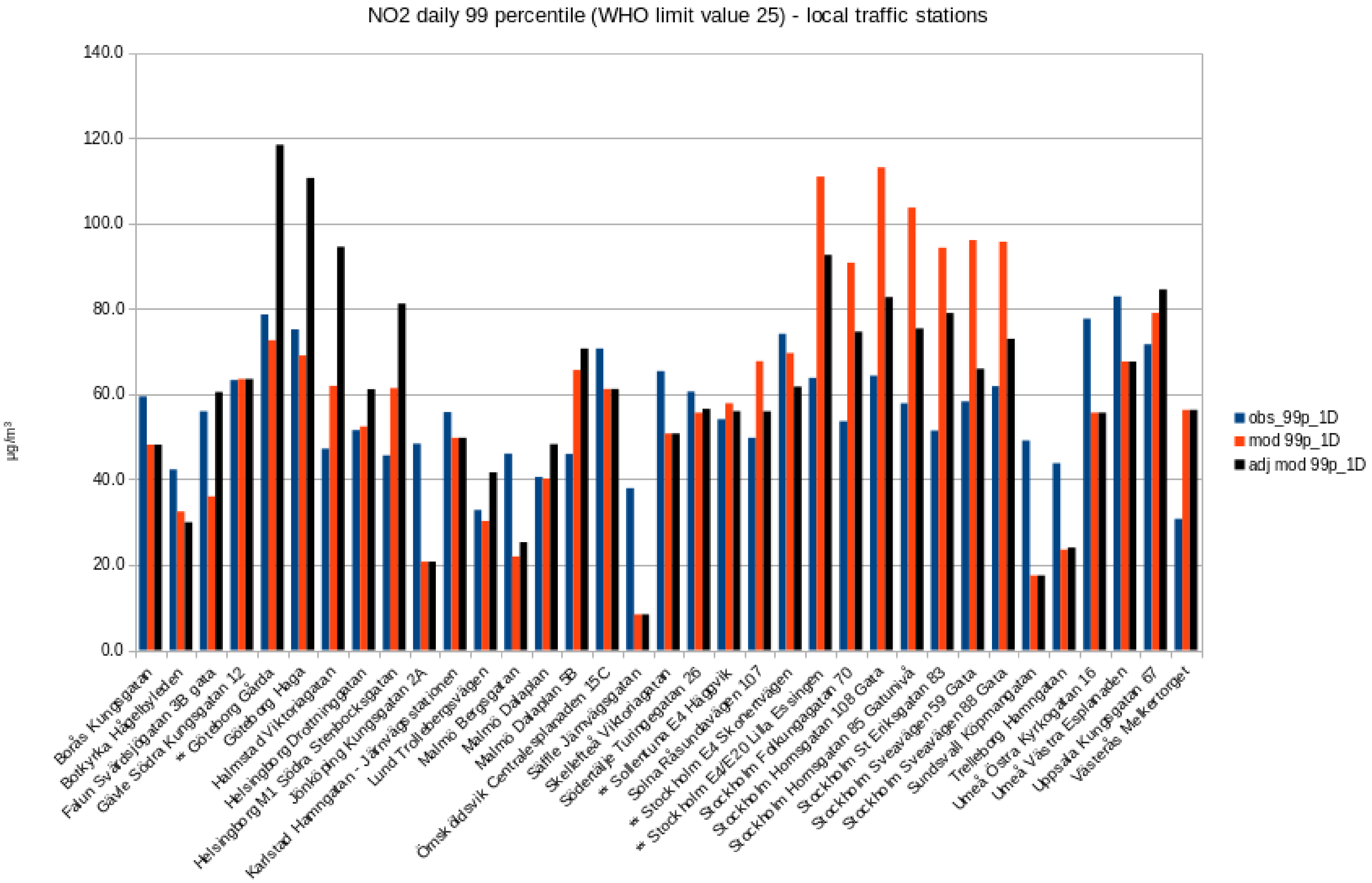

Figure 41. Modelled and observed NO_2 99^{th} percentile at local traffic sites. This is the daily limit value at 25 µg/m3 from the World Health Organisation. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

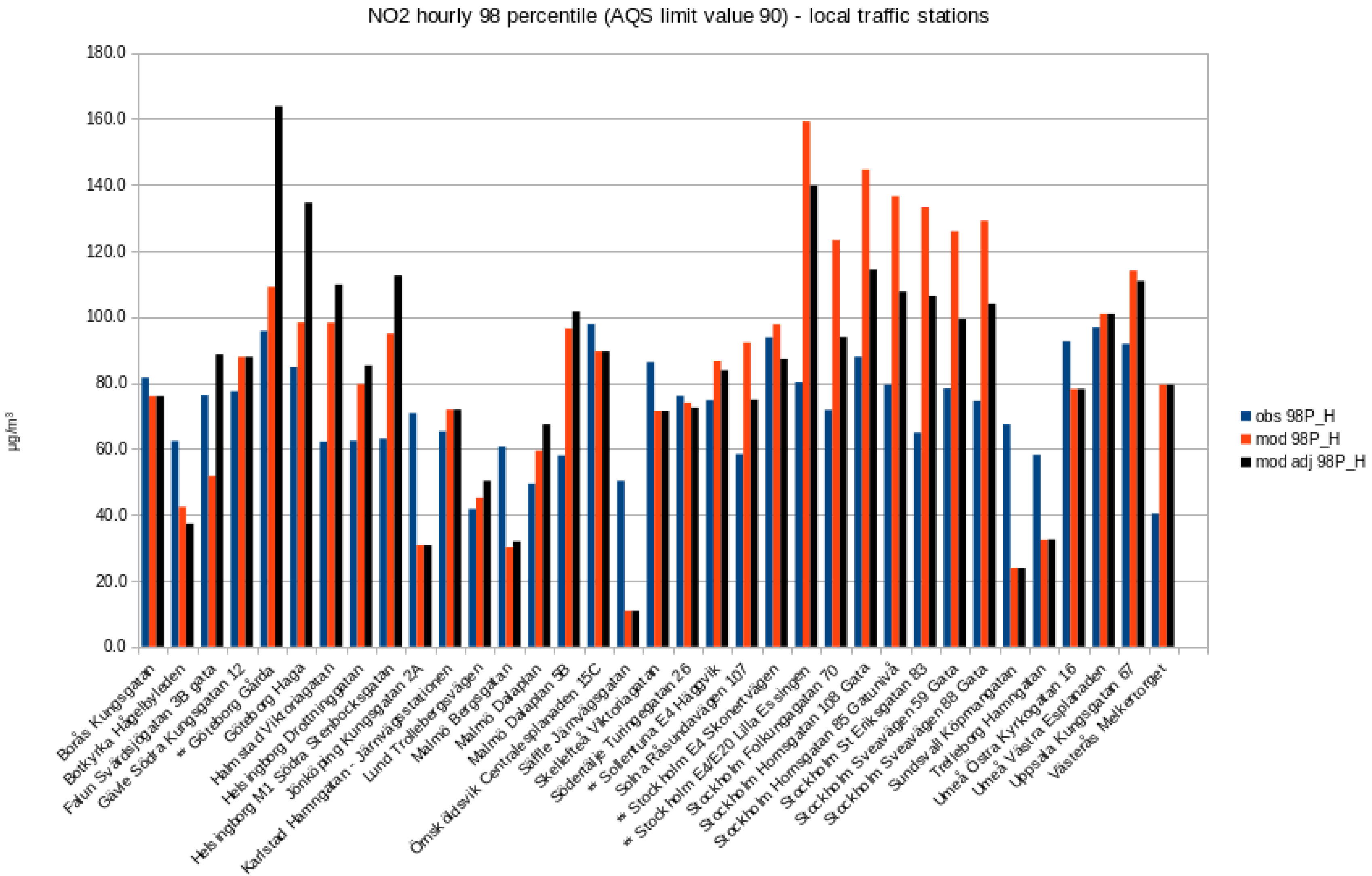

Figure 42. Modelled and observed NO_2 98th percentile at local traffic sites. This is the current hourly limit value at 90 µg/m3 in Sweden. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

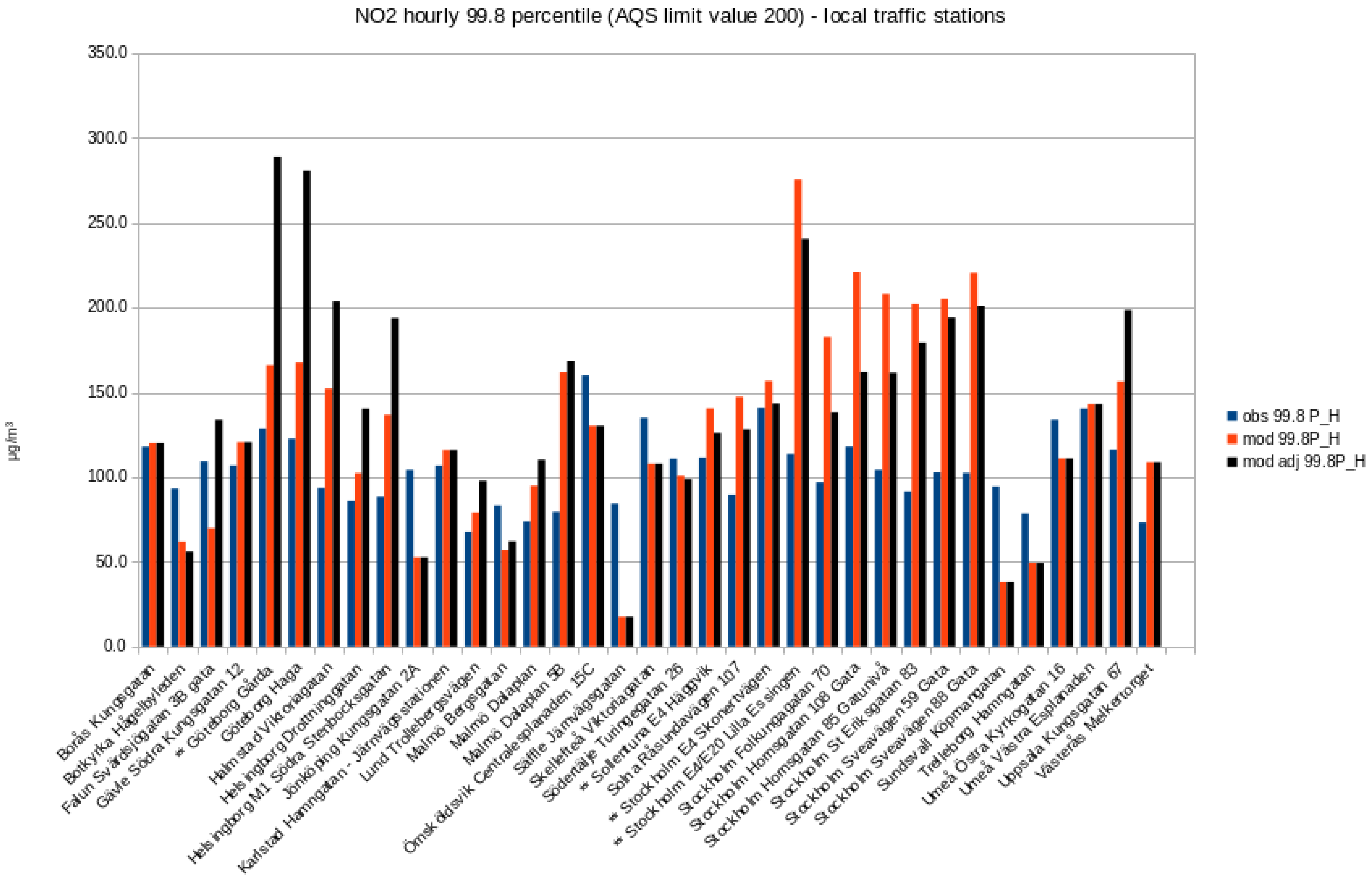

Figure 43. Modelled and observed NO_2 99.8th percentile at local traffic sites. This is the current hourly limit value at 200 µg/m3 in Sweden. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

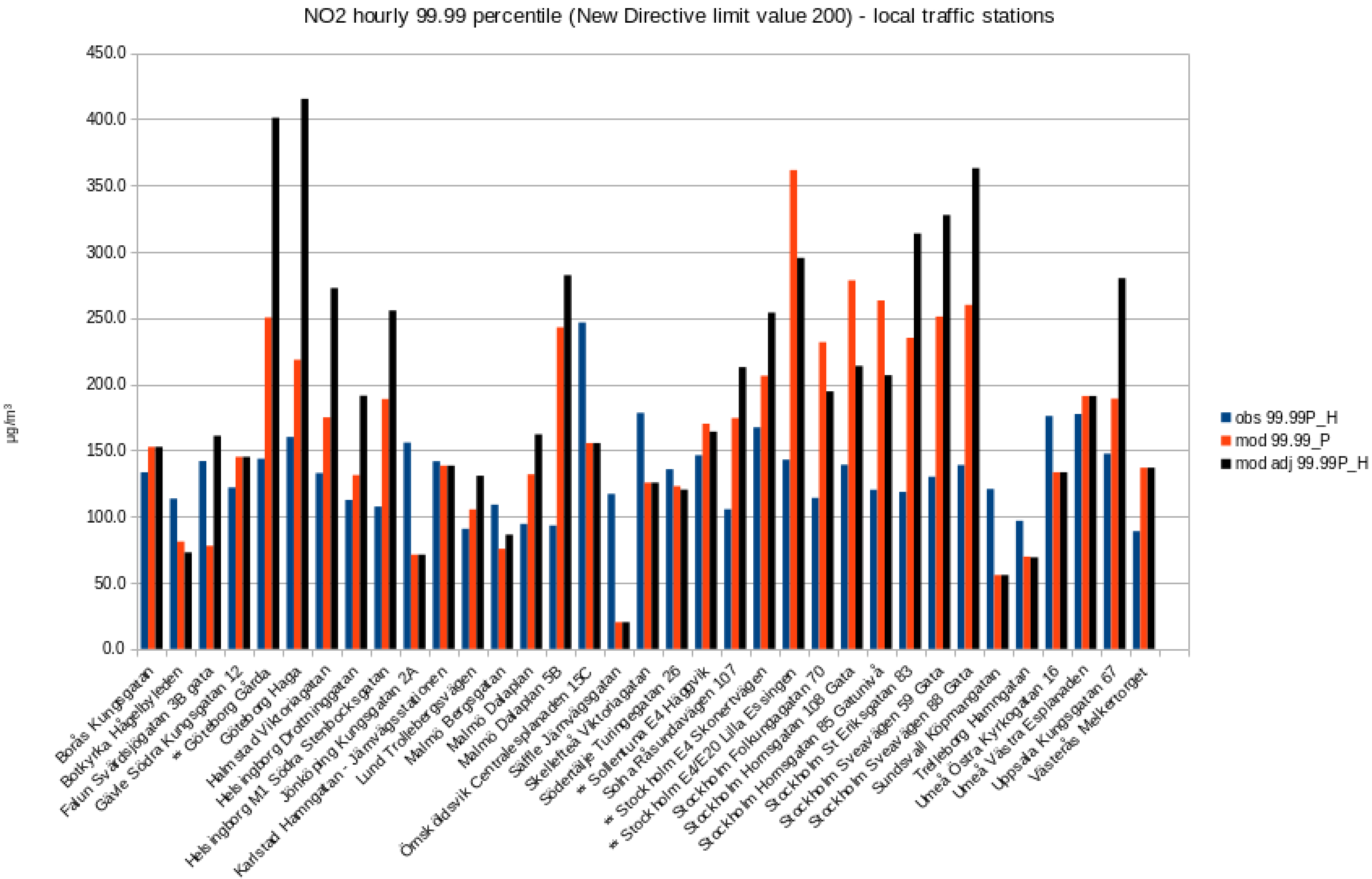

Figure 44. Modelled and observed NO_2 99.99^{th} percentile at local traffic sites. This is an update of the hourly limit value at 200 µg/m3 proposed in the revised EU Ambient Air Quality Directive. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

Appendix 2a – PM10 percentiles at urban stations

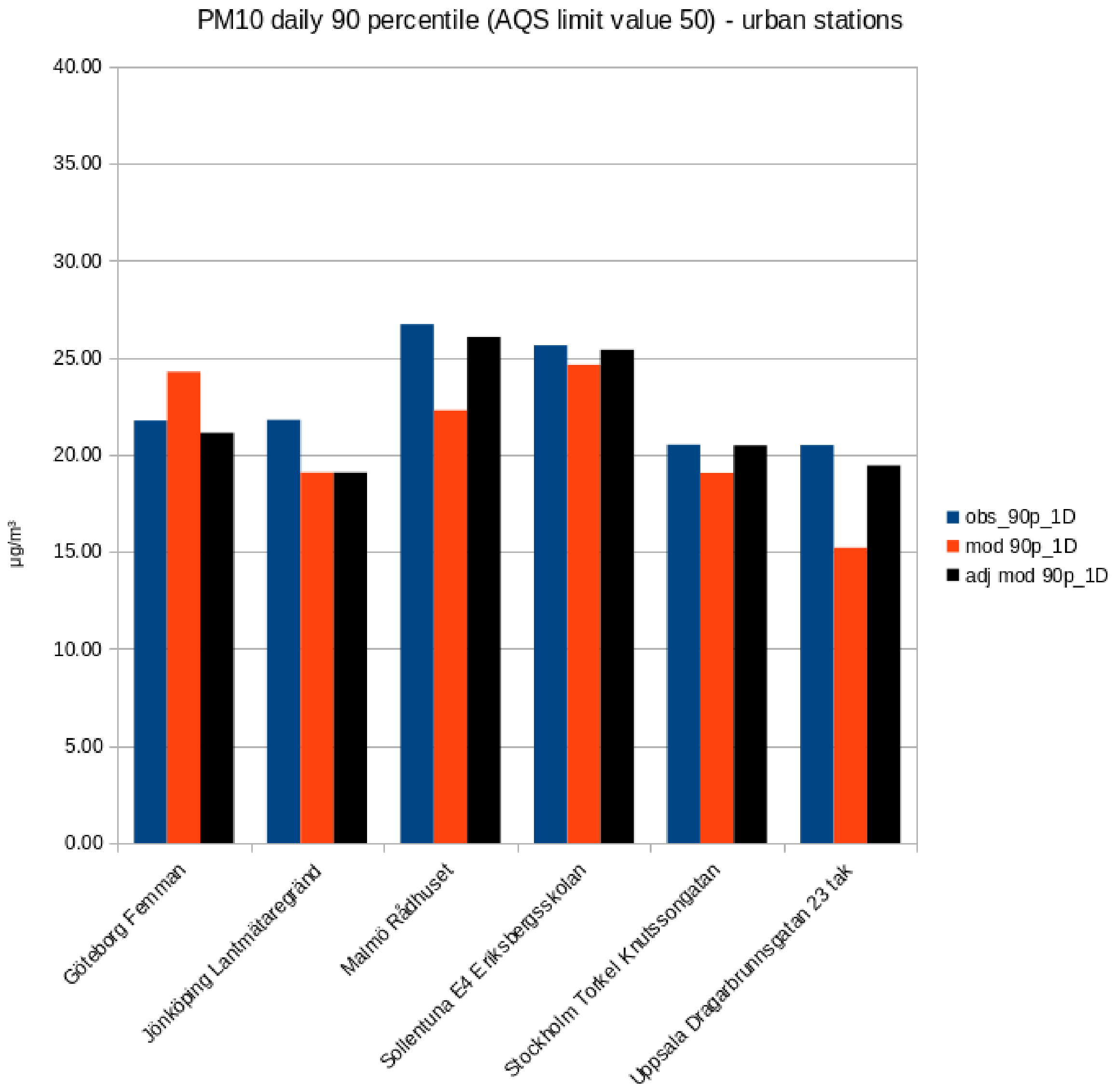

Figure 45. Modelled and observed PM10 90th percentile at urban background sites. This is the current daily limit value at 50 µg/m3. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

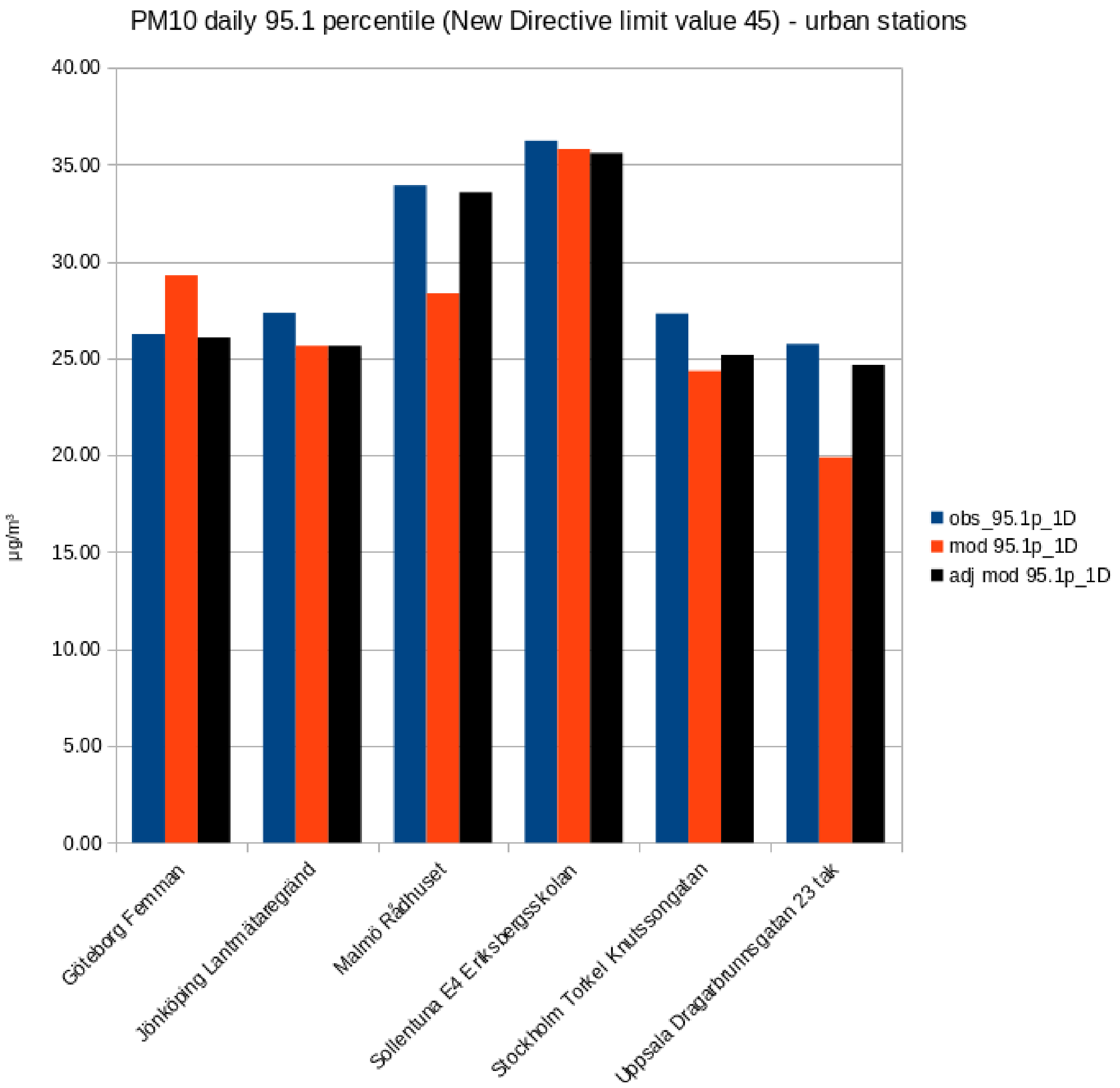

Figure 46. Modelled and observed PM10 95.1th percentile at urban background sites. This is the new daily limit value at 45 µg/m³ proposed in the revised EU Ambient Air Quality Directive. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

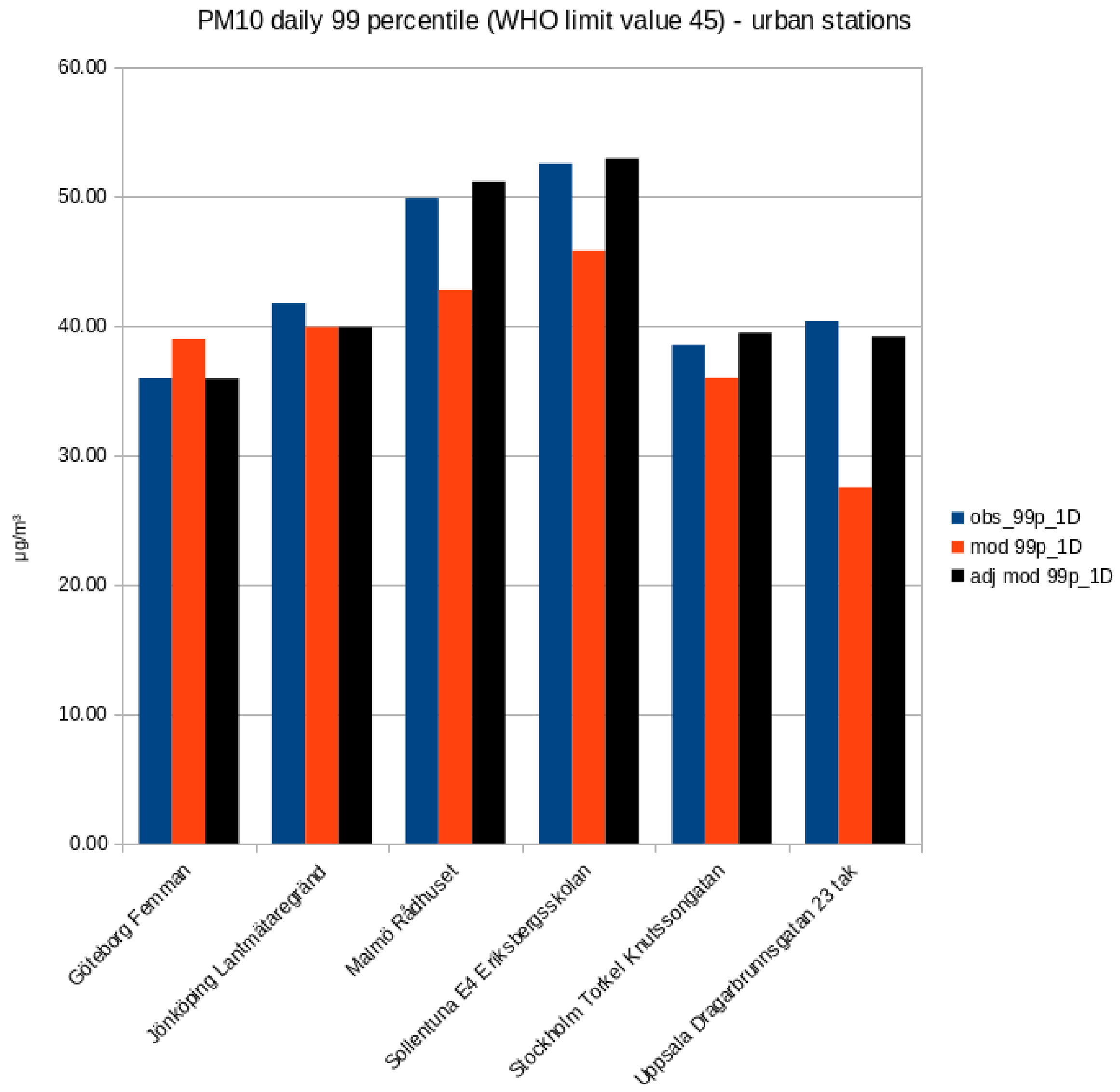

Figure 47. Modelled and observed PM10 99th percentile at urban background sites. This is the daily limit value at 45 µg/m^3 from the World Health Organisation. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

Appendix 2b – PM10 percentiles at local traffic stations

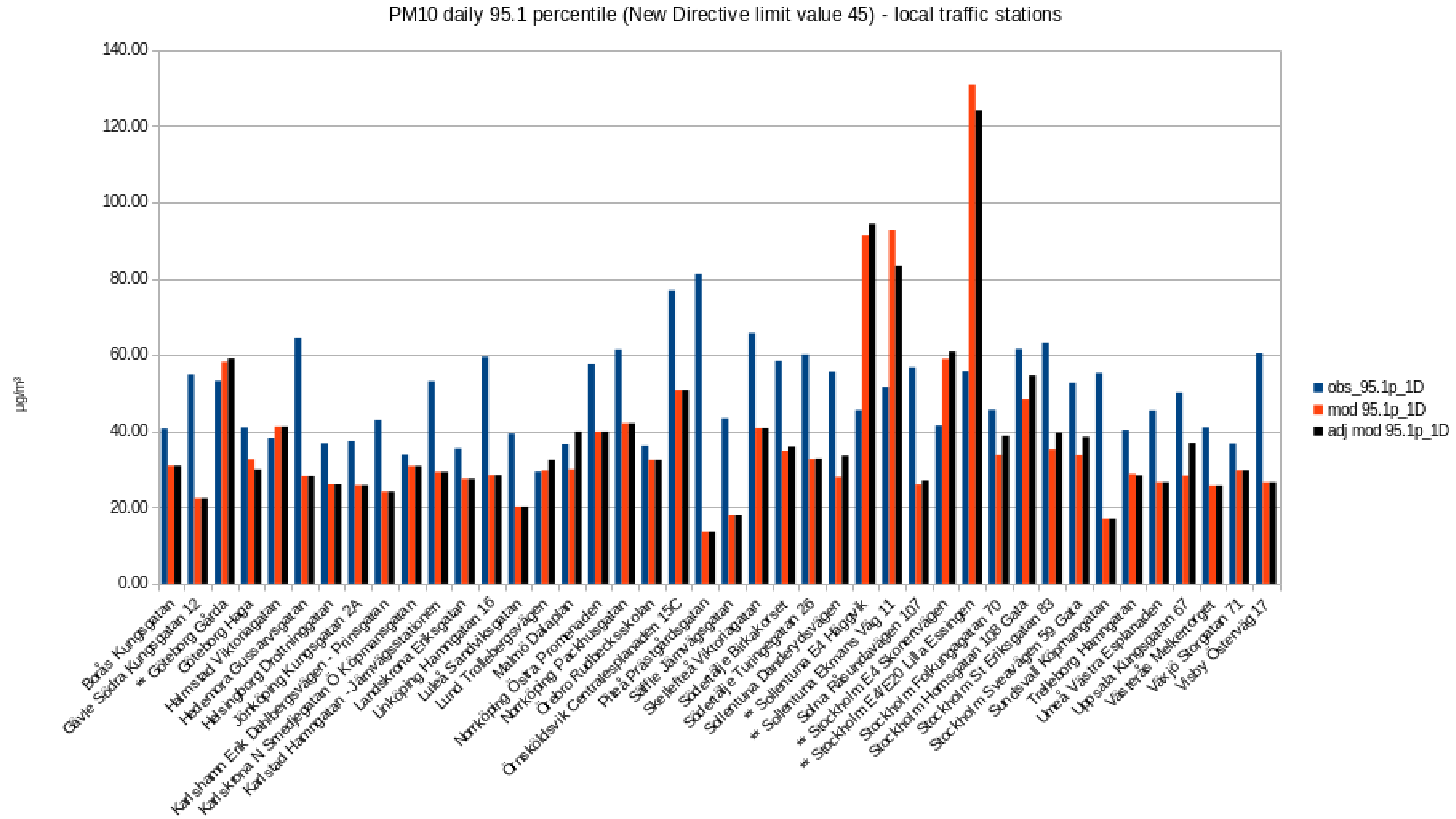

Figure 48. Modelled and observed PM10 95.1th percentile at local traffic sites. This is the new daily limit value at 45 µg/m³ proposed in the revised EU Ambient Air Quality Directive. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements.

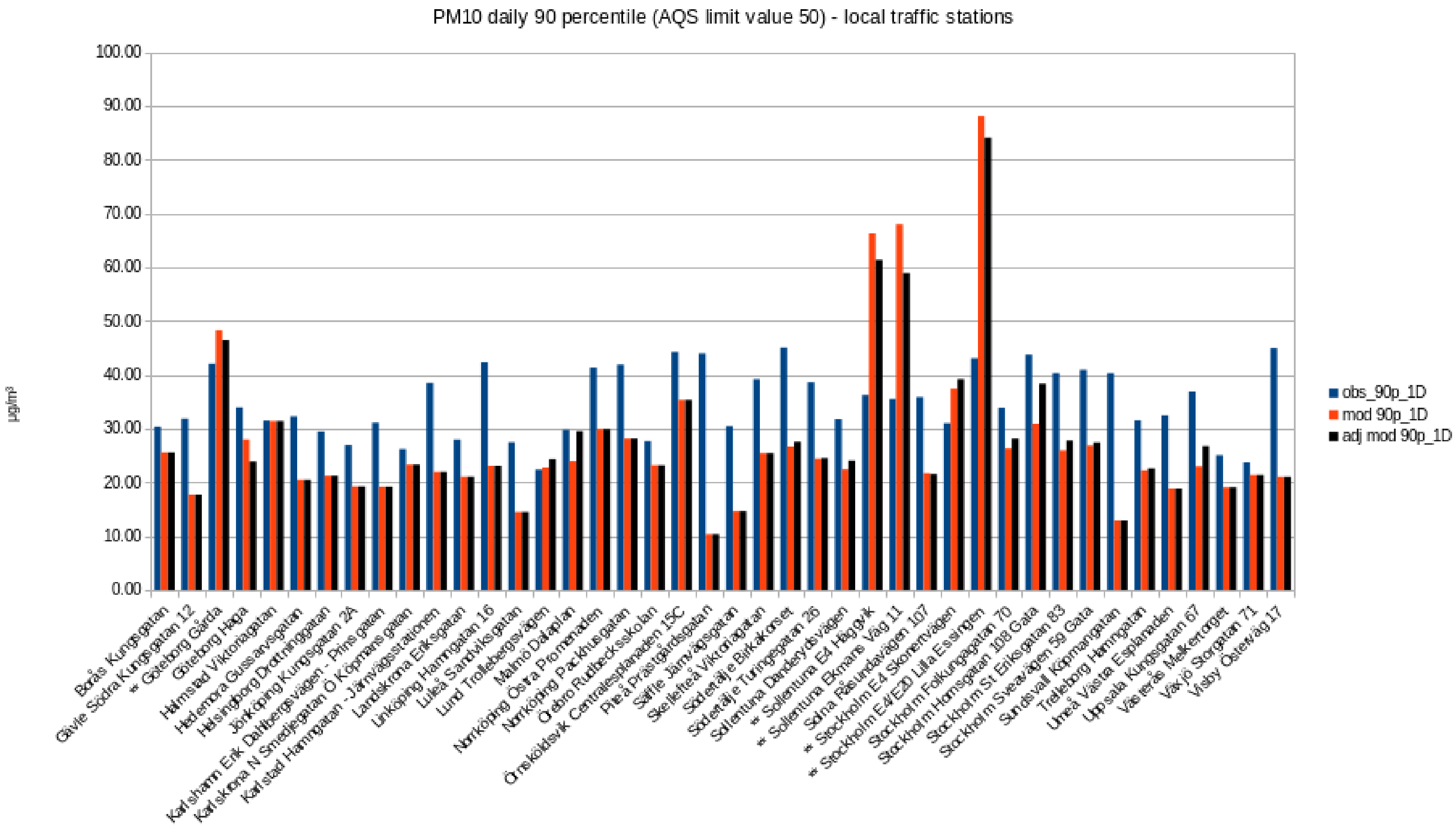

Figure 49. Modelled and observed PM10 90th percentile at local traffic sites. This is the current daily limit value at 50 µg/m^3 in Sweden. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

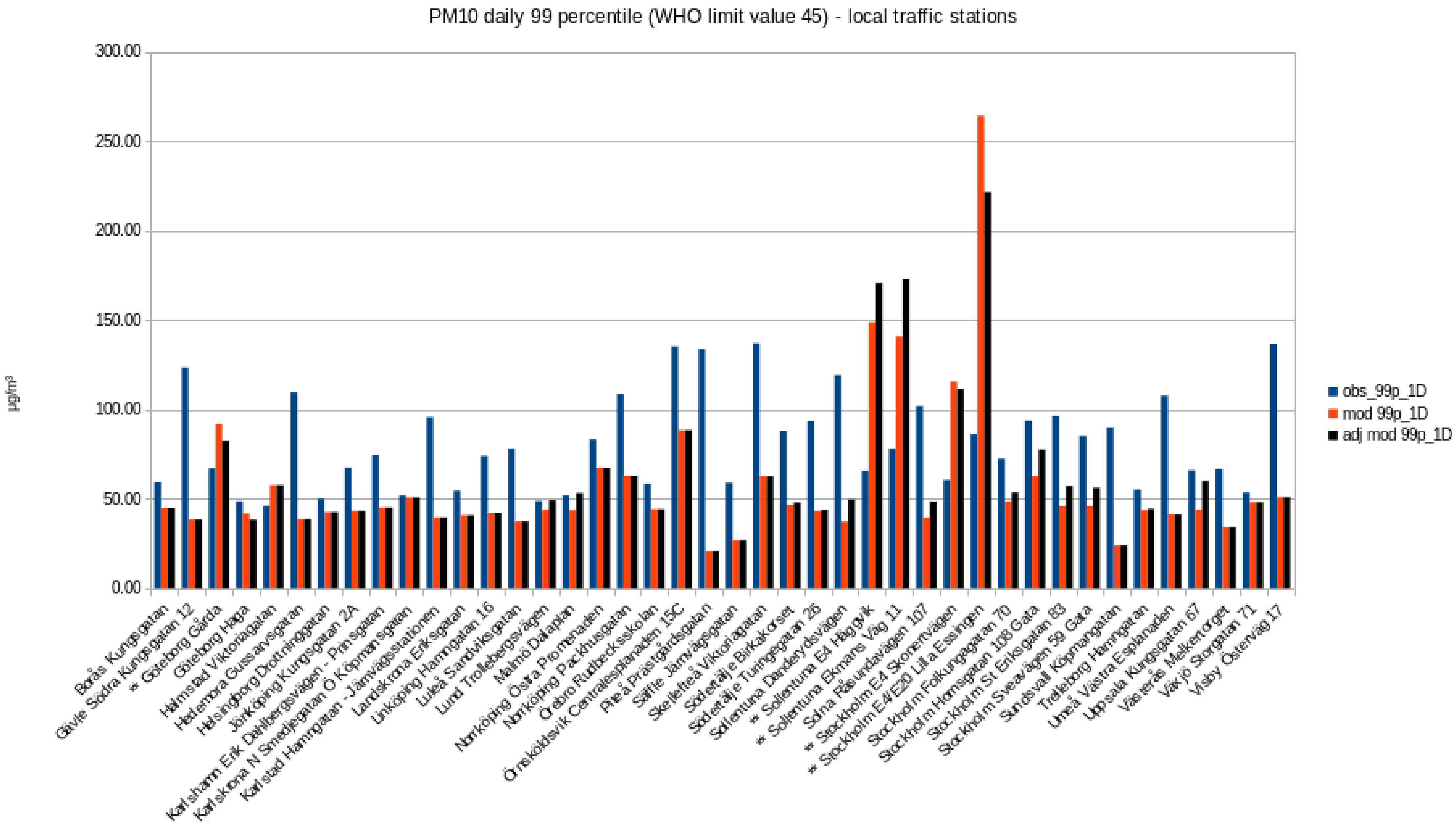

Figure 50. Modelled and observed PM10 99th percentile at local traffic sites. This is the daily limit value at 45 µg/m³ from the World Health Organisation. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

Appendix 3a – PM2.5 percentiles at urban stations

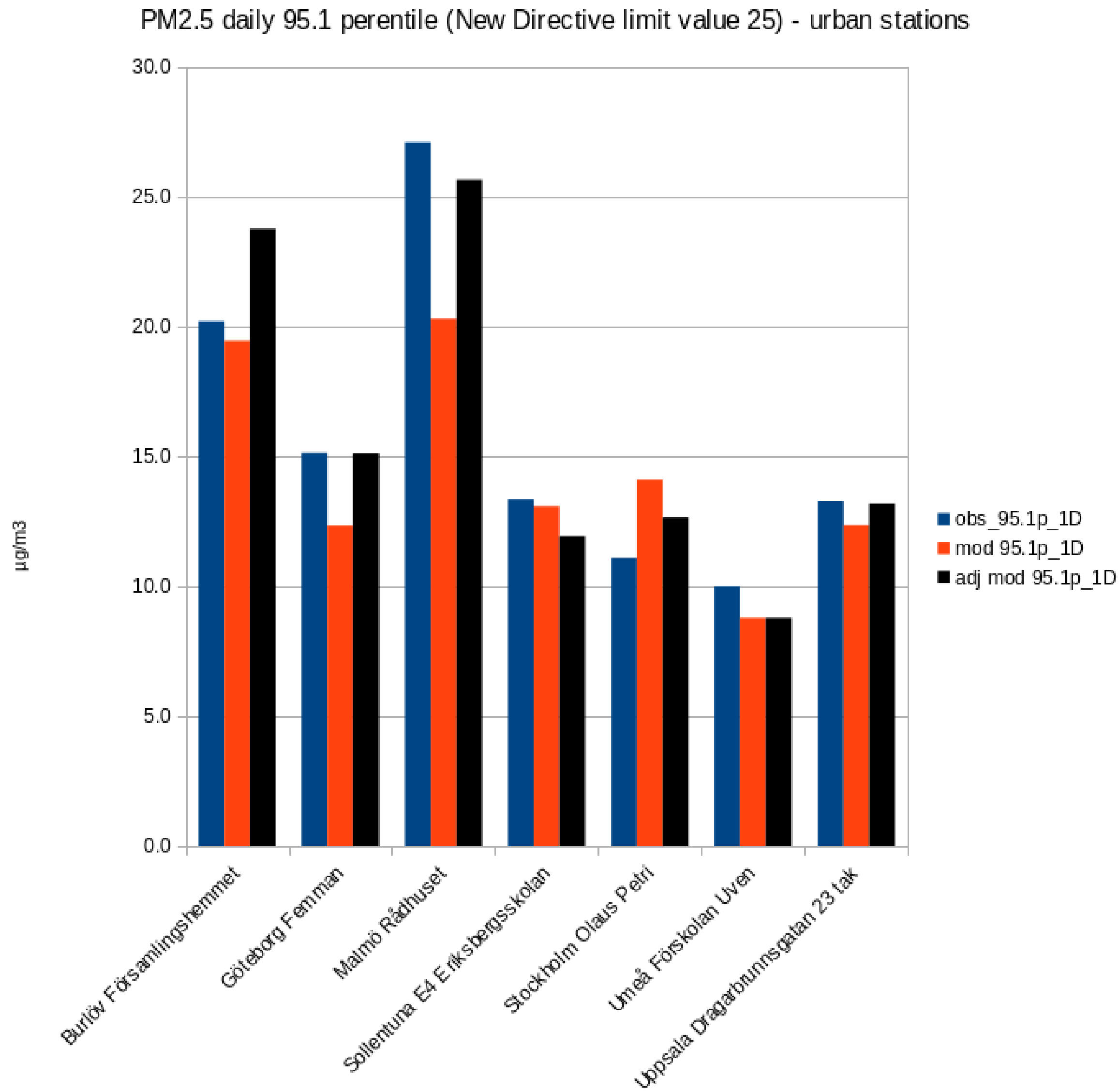

Figure 51. Modelled and observed PM2.5 95.1th percentile at urban background sites. This is the new daily limit value at 25 µg/m3 proposed in the revised EU Ambient Air Quality Directive. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

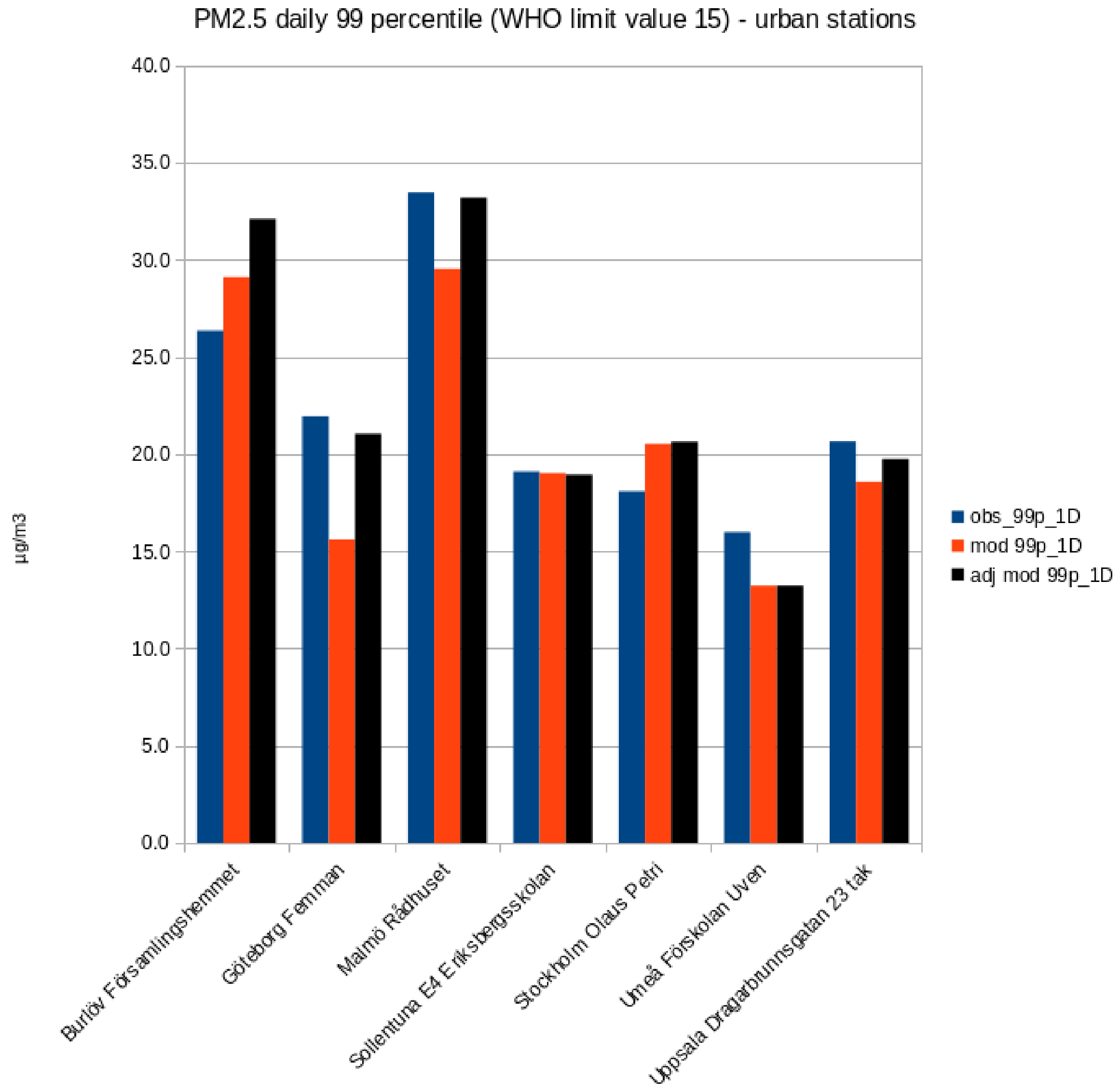

Figure 52. Modelled and observed PM2.5 99^{th} percentile at urban background sites. This is the daily limit value at 15 µg/m^3 from the World Health Organisation. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

Appendix 3b – PM2.5 percentiles at local traffic stations

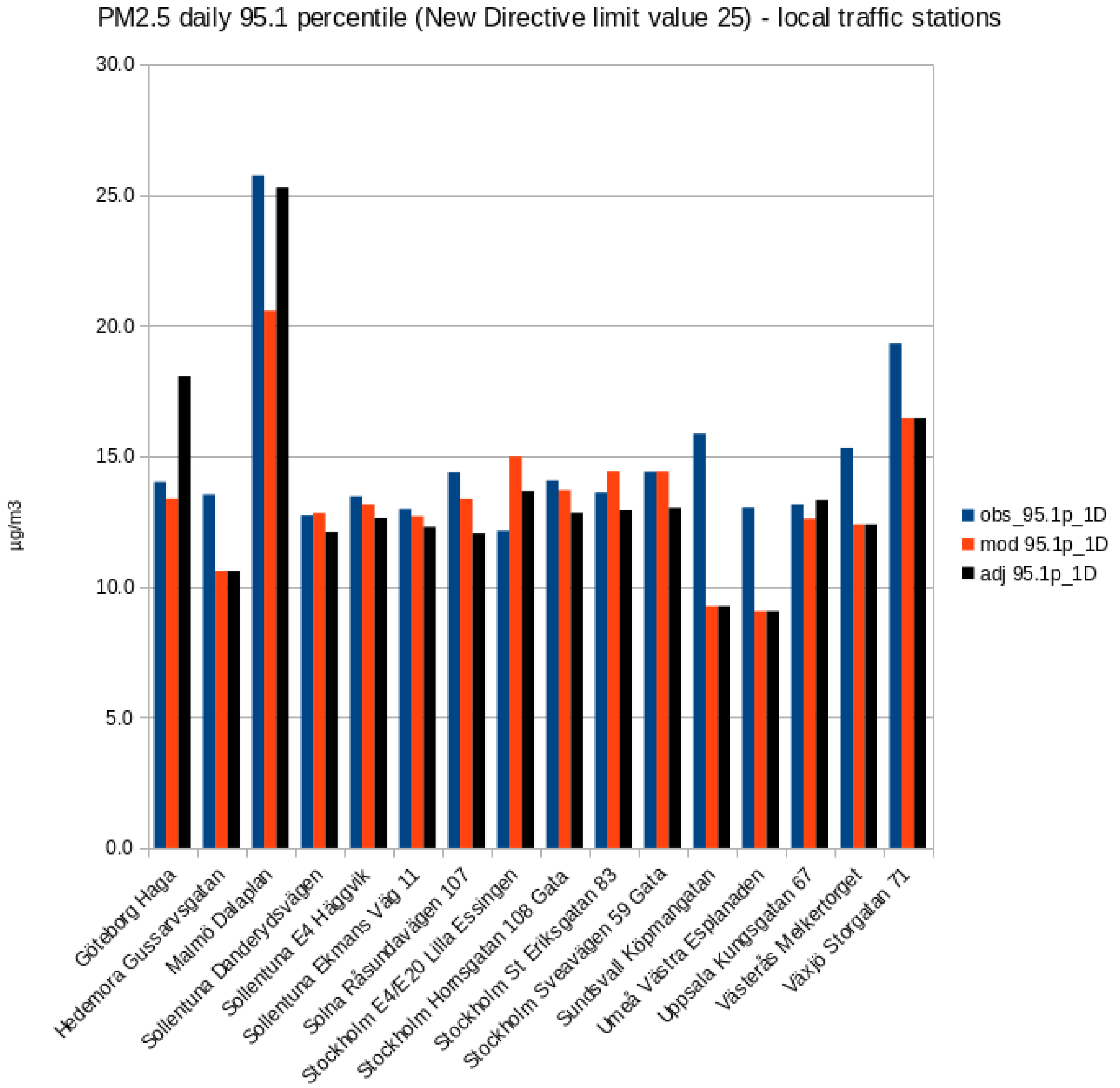

Figure 53. Modelled and observed PM2.5 95.1th percentile at local traffic sites. This is the new daily limit value at 25 µg/m3 proposed in the revised EU Ambient Air Quality Directive. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

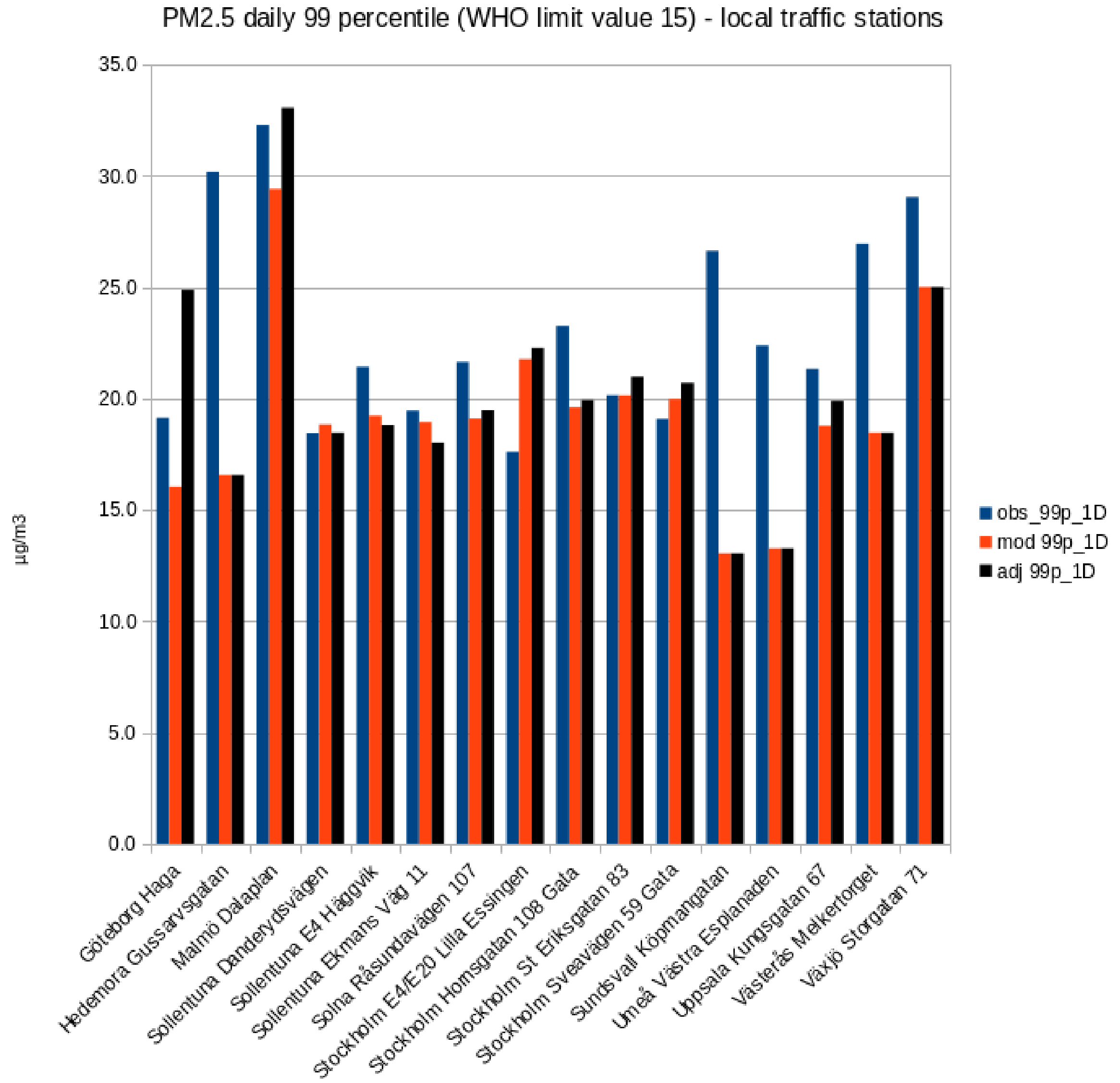

Figure 54. Modelled and observed PM2.5 99th percentile at local traffic sites. This is the daily limit value at 15 µg/m3 from the World Health Organisation. Observed (blue bars), modelled (red bars) and modelled values adjusted against urban background measurements (black bars).

8 SMHI Publications

SMHI publish seven report series. Three of these, the R-series, are intended for international readers and are in most cases written in English. For the others the Swedish language is used.

Name of the series	Published since
RMK (Report Meteorology and Climatology)	1974
RH (Report Hydrology)	1990
RO (Report Oceanography)	1986
METEOROLOGI	1985
HYDROLOGI	1985
OCEANOGRAFI	1985
KLIMATOLOGI	2009

Earlier issues published in serie RMK:

1 Thompson, T. Udin, I. and Omstedt, A. (1974)
Sea surface temperatures in waters surrounding Sweden

2 Bodin, S. (1974)
Development on an unsteady atmospheric boundary layer model

3 Moen, L. (1975)
A multi-level quasi-geostrophic model for short range weather predictions

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